

Past-paper walk-through

Calculating the Equilibrium Constant ■ 7.4

eXercise

Questions in this set

- 2026 Q3
- 2026 Q4
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- 2023 Q2
- 2022 Q2
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- 2018 Q2
- 2017 Q3
- 2014 Q4

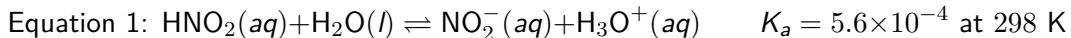
Reading the mark scheme

- **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.



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

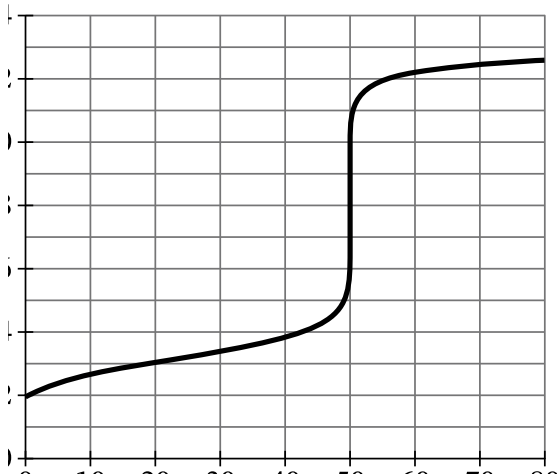
Table 1

Chemical Equation	Equilibrium Constant
$\text{HNO}_2(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NO}_2^-(aq) + \text{H}_3\text{O}^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$\text{H}_2\text{O}(l) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{OH}^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$\text{HNO}_2(aq) + \text{OH}^-(aq) \rightarrow \text{NO}_2^-(aq) + \text{H}_2\text{O}(l)$	$K_2 = ?$

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

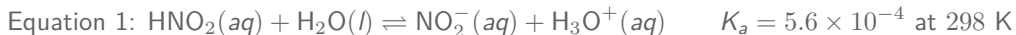
Question 3



Question 3

2026 ■ Q3

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



(b)(i) A solution of $\text{HNO}_2(aq)$ with an initial concentration of 0.125 M has a pH of 2.09.

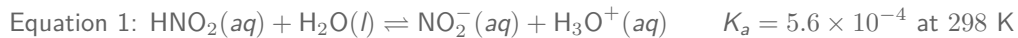
****Calculate**** the value of $[\text{H}_3\text{O}^+]$ in the solution. Show the work that leads to your answer.

(b)(ii) ****Calculate**** $[\text{HNO}_2]$ 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.



(c)(i) In an experiment, the solution of $0.125 \text{ M HNO}_2(aq)$ is heated to 333 K . The new equilibrium concentrations are determined to be $[\text{HNO}_2] = 0.114 \text{ M}$, $[\text{NO}_2^-] = 0.0109 \text{ M}$, and $[\text{H}_3\text{O}^+] = 0.0109 \text{ M}$.

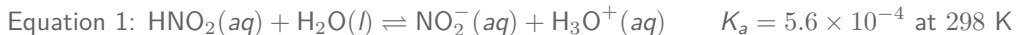
****Calculate**** the value of K_a for HNO_2 at 333 K . Show the work that leads to your answer.

(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

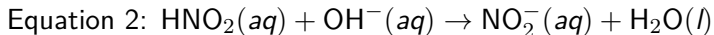
2026 ■ Q3

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



(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 $\text{HNO}_2(aq)$ in the bottle, the student titrates 35.0 mL of the $\text{HNO}_2(aq)$ with 0.16 M $\text{NaOH}(aq)$ at 298 K, which reacts according to Equation 2.



Question 3

The results of the titration are summarized in Figure 1.

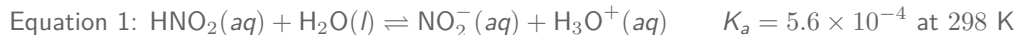
[Figure 1: Titration curve, pH vs. Volume of 0.16 M NaOH Added (mL); y-axis pH 0 to 14 in increments of 2, x-axis 0 to 80 mL in increments of 10; curve starts near (0, 2), rises gradually to about (40, 4), then rises steeply (equivalence point) between about 45-55 mL up to about pH 12, then levels off 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.

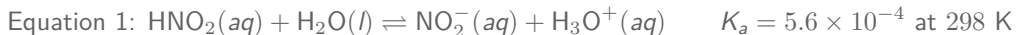


(e) Using Figure 1, ****calculate**** the molarity $\text{HNO}_2(aq)$ of in the bottle. Show the work that leads to your answer.

Question 3

2026 ■ Q3

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

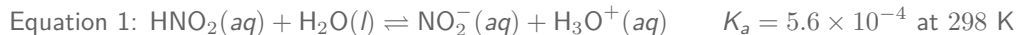


(f) ****Draw**** an X on Figure 1 to represent a point in the titration where $[\text{HNO}_2] > [\text{NO}_2^-]$ in the reaction mixture.

Question 3

2026 ■ Q3

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



(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
$\text{HNO}_2(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NO}_2^-(aq) + \text{H}_3\text{O}^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$\text{H}_2\text{O}(l) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{OH}^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$\text{HNO}_2(aq) + \text{OH}^-(aq) \rightarrow \text{NO}_2^-(aq) + \text{H}_2\text{O}(l)$	$K_2 = ?$

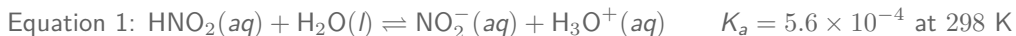
Question 3

****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.



(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

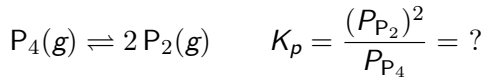
The student conducts a second titration by adding two drops of methyl orange indicator to 35.0 mL of the $\text{HNO}_2(aq)$ solution and titrating the solution with 0.16 M $\text{NaOH}(aq)$ until a color change from red to yellow occurs.

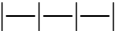
The student claims that methyl orange was the best choice for the indicator. Do you agree or disagree? ****Justify**** your answer.

Question 4

2026 ■ Q4

White phosphorus, $P_4(g)$, can decompose into $P_2(g)$ at elevated temperatures. A balanced chemical equation, K_p expression, and Lewis diagrams for the chemical species involved in the reaction are given.

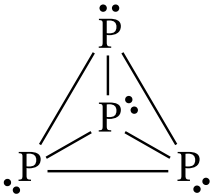


| Compound | P_4 | P_2 |  | Lewis diagram | [Tetrahedral arrangement of 4 P atoms, each bonded to the other three by single bonds, each P atom bearing one lone pair] | [$: P \equiv P :$ — a P atom triple-bonded to another P atom, each bearing one lone pair] |

Question 4

(a) The average bond length in P_4 molecules is 221 pm, whereas the average bond length in P_2 molecules is 189 pm. ****Explain**** why the average bond length in P_4 is greater than the average bond length in P_2 .

Question 4

Compound	P_4	P_2
Lewis diagram	 The diagram shows a tetrahedral arrangement of four phosphorus (P) atoms. Each P atom is connected to three other P atoms by single bonds, forming a tetrahedron. Each P atom has one lone pair of electrons, represented by two dots. The lone pairs are located at the top (for the top atom), bottom-left (for the bottom-left atom), and bottom-right (for the bottom-right atom). The bottom-center atom has its lone pair to its right.	$:P \equiv P:$

Question 4

2026 ■ Q4

White phosphorus, $P_4(g)$, can decompose into $P_2(g)$ at elevated temperatures. A balanced chemical equation, K_p expression, and Lewis diagrams for the chemical species involved in the reaction are given.



| Compound | P_4 | P_2 | $|\text{---}|\text{---}|\text{---}|$ | Lewis diagram | [Tetrahedral arrangement of 4 P atoms, each bonded to the other three by single bonds, each P atom bearing one lone pair] | [$: P \equiv P :$ — a P atom triple-bonded to another P atom, each bearing one lone pair] |

(b) A sample of $P_4(s)$ is placed in a sealed rigid container and heated to 1600. K, at which point the initial partial pressure of $P_4(g)$ is 0.470 atm. Some of the $P_4(g)$

Question 4

decomposes into $\text{P}_2(g)$ as the system reaches equilibrium. At equilibrium, the partial pressure of $\text{P}_2(g)$ is determined to be 0.630 atm.

****Calculate**** the value of the equilibrium constant, K_p , for the reaction at 1600. K. Show the work that leads to your answer.

Question 4

2026 ■ Q4

White phosphorus, $P_4(g)$, can decompose into $P_2(g)$ at elevated temperatures. A balanced chemical equation, K_p expression, and Lewis diagrams for the chemical species involved in the reaction are given.



| Compound | P_4 | P_2 | $|\text{---}|\text{---}|\text{---}|$ | Lewis diagram | [Tetrahedral arrangement of 4 P atoms, each bonded to the other three by single bonds, each P atom bearing one lone pair] | [$: P \equiv P :$ — a P atom triple-bonded to another P atom, each bearing one lone pair] |

(c) The reaction is thermodynamically favorable under standard conditions only at temperatures above 1500 K. A student claims that the reaction must be endothermic

Question 4

because it is favorable only at high temperatures. Do you agree or disagree?

****Justify**** your answer using ΔS°_{rxn} and ΔG°_{rxn} .

Question 3

2025 ■ Q3

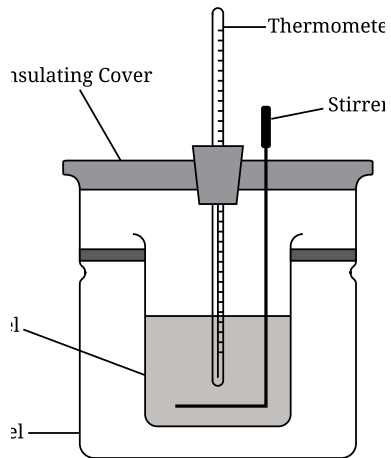
White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(a) In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.

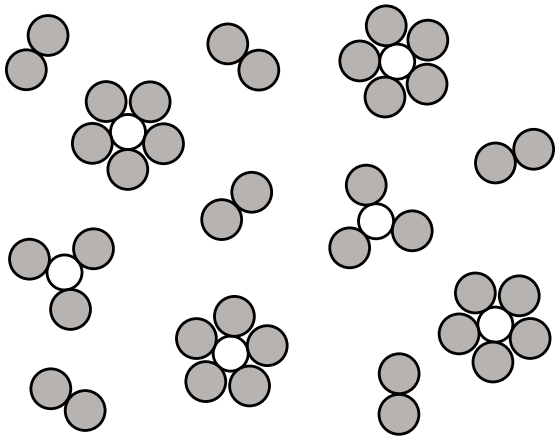
Question 3



Question 3

Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	22.00° C
Final temperature	22.38° C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g·°C)

Question 3



Question 3

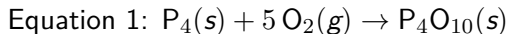
2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(b) The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.



Question 3

(b)(i) The entropy change of the reaction, ΔS° , is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.

(b)(ii) The enthalpy change of the reaction, ΔH° , is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between ΔG° , ΔH° , and ΔS° .

Question 3

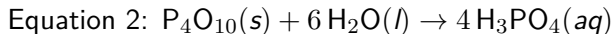
2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(c) $P_4O_{10}(s)$ reacts exothermically with water to form phosphoric acid, as represented by equation 2.



Question 3

A chemist uses a calorimetry experiment to determine the enthalpy change for the reaction, as represented by the following diagram.

[Calorimeter diagram: a coffee-cup-style calorimeter labeled "Thermometer" (inserted through the insulating cover), "Stirrer" (inserted alongside the thermometer), "Insulating Cover" (the lid), "Inner Vessel" (the cup holding the solution, shaded), and "Outer Vessel" (the outer supporting cup).]

The chemist carries out the calorimetry experiment and records the following information.

Quantity	Value	—	—	Mass of P_4O_{10}	0.100 g	Mass of H_2O	100.0 g
Initial temperature	22.00°C	Final temperature	22.38°C	Molar mass of P_4O_{10}	283.9 g/mol	Specific heat of H_2O	4.18 J/(g · °C)

(c)(i) Calculate the amount of heat, q , released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.

Question 3

(c)(ii) Calculate the value of ΔH_{rxn}° for equation 2 in kJ/mol_{rxn} . Include the sign in your answer.

Question 3

2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(d) The chemist weighed out 0.100 g P_4O_{10} of and 100.0 g of H_2O to perform a second trial. In the second trial, some of the solid P_4O_{10} stuck to the weighing paper and was not transferred to the calorimeter. Given that P_4O_{10} is the limiting reactant,

Question 3

would ΔT for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

$\text{P}_4(\text{s})$ also reacts readily with $\text{Cl}_2(\text{g})$ to produce phosphorus trichloride, $\text{PCl}_3(\text{g})$, which in turn reacts with $\text{Cl}_2(\text{g})$ in an equilibrium process to produce $\text{PCl}_5(\text{g})$. The reactions are represented by equations 3 and 4.



Question 3

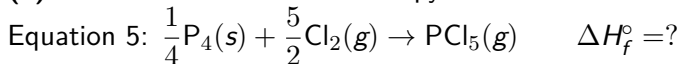
2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(e) Calculate the standard enthalpy of formation of $PCl_5(g)$ represented by equation 5.



The following particle-level diagram represents the contents of the vessel in an equilibrium mixture at 546 K involving equation 4.

Question 3

[Particle diagram: a box containing multiple particles at random positions representing an equilibrium mixture; a key indicates two-atom particles (grey-grey) = Cl_2 , four-atom tetrahedral-looking particles (grey with three white) = PCl_3 , and six-atom particles (grey with five white) = PCl_5 . The box shows several Cl_2 particles (pairs of grey circles), several PCl_3 particles (grey center with three white circles), and several PCl_5 particles (grey center with five white circles) scattered throughout.]

Question 3

2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(f) Equation 4 for the reaction that occurs is shown.



(f)(i) If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of K_p for the equilibrium mixture at 546 K?

Question 3

(f)(ii) Does the value of K_p increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on ΔH_2° .

Solution 3

(a)

Mark scheme

- Complete Lewis diagram for P_4 : the four P atoms form a tetrahedron, each bonded to the other three P atoms by single bonds, and each P atom bears one lone (nonbonding) pair of electrons — giving each P three bonding pairs plus one lone pair, satisfying the octet rule.

Solution 3

(b)

Mark scheme

- No separate response required — this is the context/stem presenting equation 1 ($\text{P}_4(\text{s}) + 5 \text{O}_2(\text{g}) \rightarrow \text{P}_4\text{O}_{10}(\text{s})$), thermodynamically favorable at 298 K, that parts (i) and (ii) below refer to.

(b)(i)

Mark scheme

- Because gas particles are more dispersed (have more accessible microstates) than solids, the entropy decreases as the reactants (which include a gas, O_2) convert into the solid product (P_4O_{10}).

Solution 3

(b)(ii)

Mark scheme

- Yes, the student's claim is correct. Given $\Delta G_{rxn}^{\circ} = \Delta H_{rxn}^{\circ} - T\Delta S_{rxn}^{\circ}$, the reaction must have $\Delta G_{rxn}^{\circ} < 0$ to be favorable. Because the reaction is exothermic, $\Delta H_{rxn}^{\circ} < 0$ and enthalpy contributes to favorability. $\Delta S_{rxn}^{\circ} < 0$, so entropy does NOT contribute to favorability — i.e., enthalpy alone drives it.

Solution 3

(c)

Mark scheme

- No separate response required — this is the context/stem describing the calorimetry experiment for the exothermic reaction of $\text{P}_4\text{O}_{10}(\text{s})$ with water (equation 2: $\text{P}_4\text{O}_{10}(\text{s}) + 6 \text{H}_2\text{O}(\text{l}) \rightarrow 4 \text{H}_3\text{PO}_4(\text{aq})$) that parts (i) and (ii) below use.

Solution 3

(c)(i)

Mark scheme

- $q = mc\Delta T = (100.1 \text{ g})(4.18 \text{ J/(g}\cdot^{\circ}\text{C)})(22.38^{\circ}\text{C} - 22.00^{\circ}\text{C}) = 160 \text{ J} = 0.16 \text{ kJ}$
(reported to the correct number of significant figures).

Solution 3

(c)(ii)

Mark scheme

■ $q_{rxn} = -q_{surr} = -0.16 \text{ kJ}.$

$$\Delta H_{rxn}^{\circ} = \frac{-0.16 \text{ kJ}}{0.100 \text{ g P}_4\text{O}_{10}} \times \frac{283.9 \text{ g P}_4\text{O}_{10}}{1 \text{ mol P}_4\text{O}_{10}} \times \frac{1 \text{ mol P}_4\text{O}_{10}}{1 \text{ mol}_{rxn}} = -450 \text{ kJ/mol}_{rxn}.$$

The correct (negative) sign must be included.

Solution 3

(d)

Mark scheme

- Less than. If less P_4O_{10} is present (some stuck to the weighing paper), less thermal energy will be transferred to the water during the reaction, causing the temperature increase (ΔT) to be less than it was with the full 0.100 g of P_4O_{10} .

Solution 3

(e)

Mark scheme

- Using Hess's law:

$$\Delta H_{f,\text{PCl}_5(g)}^\circ = \frac{1}{4}\Delta H_1^\circ + \Delta H_2^\circ = \frac{1}{4}(-1148) + (-88) = -375 \text{ kJ/mol.}$$

Solution 3

(f)

Mark scheme

- No separate response required — this is the context/stem presenting equation 4 ($\text{PCl}_3(g) + \text{Cl}_2(g) \rightleftharpoons \text{PCl}_5(g)$, $\Delta H_2^\circ = -88 \text{ kJ/mol}_{\text{rxn}}$) that parts (i) and (ii) below refer to.

Solution 3

(f)(i)

Mark scheme

- Reading partial pressures of 1.00 atm per particle from the diagram (4 PCl_5 , 2 PCl_3 , 6 Cl_2 particles): $K_p = \frac{P_{\text{PCl}_5}}{(P_{\text{PCl}_3})(P_{\text{Cl}_2})} = \frac{4.00}{(2.00)(6.00)} = \frac{1}{3} = 0.333$.

Solution 3

(f)(ii)

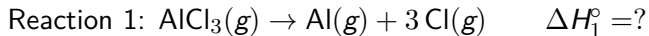
Mark scheme

- Decrease. The negative value of ΔH_2° indicates the reaction is exothermic. Because exothermic reactions favor reactant formation at higher temperature (the equilibrium shifts toward reactants as heat is added), the value of K_p decreases.

Question 2

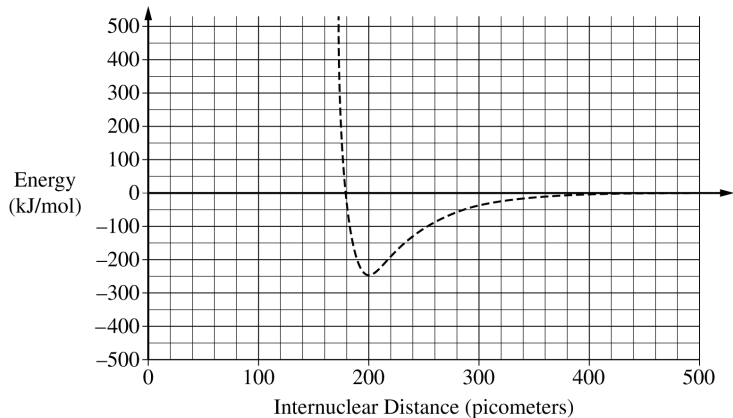
2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



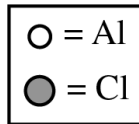
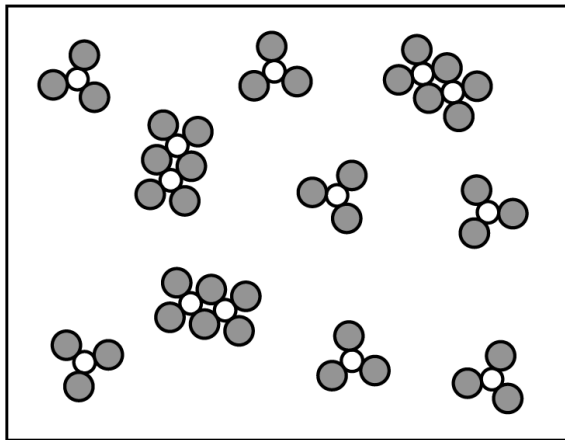
(a) How many grams of $\text{Cl}(g)$ can be formed from 1.25 mol of $\text{AlCl}_3(g)$?

Question 2



on the graph, what is the bond length, in picometers, for Cl_2 ? _____

Question 2



Question 2

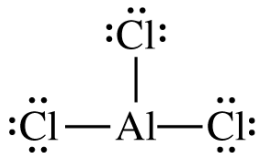


Diagram 1

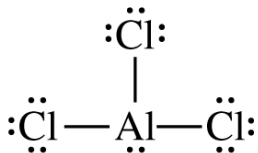


Diagram 2

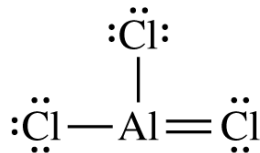


Diagram 3

Question 2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.

(b) Additional reactions that involve Al or Cl are shown in the following table.

Reaction Number	Equation	ΔH_{rxn}° (kJ/mol _{rxn})	2
	$\text{Al}(s) + \frac{3}{2}\text{Cl}_2(g) \rightarrow \text{AlCl}_3(g)$	-583	3
	$\text{Al}(s) \rightarrow \text{Al}(g)$	+326	4
	$\text{Cl}_2(g) \rightarrow 2\text{Cl}(g)$	+243	

Calculate the value of ΔH_1° , in kJ/mol_{rxn}, for reaction 1 above using reactions 2, 3, and 4.

Question 2

2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



(c)(i) A potential energy diagram for Cl_2 is shown in the following graph.

[Graph: potential energy (kJ/mol) vs. internuclear distance (picometers) for Cl_2 ; y-axis from -500 to 500 kJ/mol in steps of 100 ; x-axis from 0 to 500 picometers in steps of 100 ; dashed curve starts high near $x = 0$, plunges to a minimum of about -250 kJ/mol near $x \approx 200$ pm, then rises and levels off near 0 kJ/mol as x increases toward 500 pm.]

Based on the graph, what is the bond length, in picometers, for Cl_2 ?

Question 2

(c)(ii) A student finds that the average Al – Cl bond length is 220 picometers and the average bond energy is 425 kJ/mol. Draw the potential energy curve for the average Al – Cl bond on the preceding graph.

Question 2

2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



(d)(i) Three proposed Lewis diagrams for the $\text{AlCl}_3(g)$ molecule are shown.

[Diagram 1: Cl bonded to Al with a single bond above (Cl with 3 lone pairs) and two Cl atoms bonded to Al with single bonds on either side (each Cl with 3 lone pairs) — trigonal arrangement, all single Al–Cl bonds, Al with no lone pair shown.] [Diagram 2: same trigonal arrangement of three Cl atoms singly bonded to Al, each Cl shown with 3 lone pairs — visually similar layout to Diagram 1.] [Diagram 3: two Cl atoms singly bonded to Al (each with 3 lone pairs) and one Cl atom double-bonded to Al (shown with 2 lone pairs) — $\text{Cl}=\text{Al}$ on the right side.]

Diagram 1, Diagram 2, Diagram 3 (labeled beneath each structure).

Question 2

The $\text{AlCl}_3(g)$ molecule has a trigonal planar geometry. Which diagram (1, 2, or 3) can be eliminated based on geometry? Justify your choice based on VSEPR theory.

(d)(ii) Which of the three diagrams is the best representation for the bonding in AlCl_3 ? Justify your choice based on formal charges.

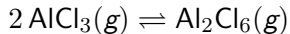
Question 2

2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



(e) AlCl_3 is known to dimerize reversibly in the gas phase. The dimerization equilibrium is represented by the following equation.



Write the expression for the equilibrium constant, K_p , for this reaction.

Question 2

2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



(f) A particle-level diagram of an equilibrium mixture of $\text{AlCl}_3(g)$ and $\text{Al}_2\text{Cl}_6(g)$ at 400°C in a 25 L closed container is shown.

[Particle diagram inside a rectangular box: several clusters of gray/white circles representing AlCl_3 monomers (isolated groupings of 1 white Al + 3 gray Cl) and Al_2Cl_6 dimers (larger fused clusters of 2 white Al + 6 gray Cl), scattered throughout the container. Legend: white circle = Al, gray circle = Cl.]

Using the particle-level diagram, calculate the value of K_p for the reaction if the total pressure in the container is 22.1 atm.

Solution 2

(a)

Mark scheme

$$\blacksquare 1.25 \text{ mol AlCl}_3 \times \frac{3 \text{ mol Cl}}{1 \text{ mol AlCl}_3} \times \frac{35.45 \text{ g Cl}}{1 \text{ mol Cl}} = 133 \text{ g Cl (3 sig figs)}.$$

Solution 2

(b) Mark scheme

- Apply Hess's law using reactions 2, 3, and 4: reverse reaction 2 ($\text{AlCl}_3(g) \rightarrow \text{Al}(s) + \frac{3}{2}\text{Cl}_2(g)$, $\Delta H = -(-583) = +583 \text{ kJ/mol}_{\text{rxn}}$) and multiply reaction 4 by $\frac{3}{2}$ ($\frac{3}{2}\text{Cl}_2(g) \rightarrow 3 \text{ Cl}(g)$, $\Delta H = 1.5(+243) = +365 \text{ kJ/mol}_{\text{rxn}}$), then add reaction 3 unchanged:
$$\Delta H_1^\circ = -\Delta H_2^\circ + \Delta H_3^\circ + 1.5(\Delta H_4^\circ) = -(-583) + 326 + 1.5(243) = 1274 \text{ kJ/mol}_{\text{rxn}}.$$

Solution 2

(c)(i)

Mark scheme

- Bond length ≈ 200 picometers (± 10 pm), read from the internuclear distance at the minimum (lowest potential energy point) of the Cl_2 curve shown.

Solution 2

(c)(ii)

Mark scheme

- Draw a new potential-energy curve for the Al–Cl bond with its minimum at an internuclear distance of 220 ± 10 pm — longer than Cl_2 's 200 pm bond length (1 point) — and a minimum energy value of -425 ± 20 kJ/mol that approaches zero as the internuclear distance approaches 500 pm — a shallower well than Cl_2 's since the Al–Cl bond energy (425 kJ/mol) is less than the Cl–Cl bond energy shown on the original curve (1 point).

Solution 2

(d)(i)

Mark scheme

- Diagram 2 is not a valid representation. In Diagram 2, Al has four electron domains (three single Al–Cl bonds plus one lone pair on Al), which would give a trigonal pyramidal (not trigonal planar) molecular geometry — inconsistent with the known trigonal planar geometry of $\text{AlCl}_3(\text{g})$.

Solution 2

(d)(ii)

Mark scheme

- Diagram 1 is the best representation. All atoms in Diagram 1 have a formal charge of zero, whereas atoms in Diagrams 2 and 3 have nonzero formal charges — the Lewis structure that minimizes (here, eliminates) formal charges is preferred.

Solution 2

(e)

Mark scheme

$$\blacksquare K_p = \frac{P_{\text{Al}_2\text{Cl}_6}}{(P_{\text{AlCl}_3})^2}.$$

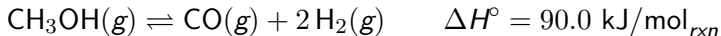
Solution 2

(f) Mark scheme

- Using mole fractions read from the particle diagram ($\chi_{\text{AlCl}_3} = \frac{7}{10}$, $\chi_{\text{Al}_2\text{Cl}_6} = \frac{3}{10}$) and total pressure 22.1 atm: $K_p = \frac{\chi_{\text{Al}_2\text{Cl}_6}(P_{\text{total}})}{(\chi_{\text{AlCl}_3}(P_{\text{total}}))^2} = \frac{\frac{3}{10}(22.1)}{(\frac{7}{10}(22.1))^2} = 0.0277$.

Question 2

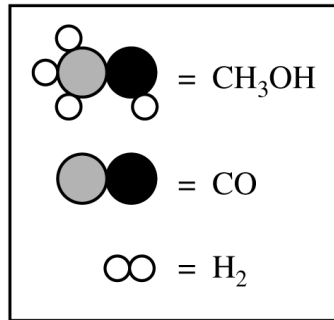
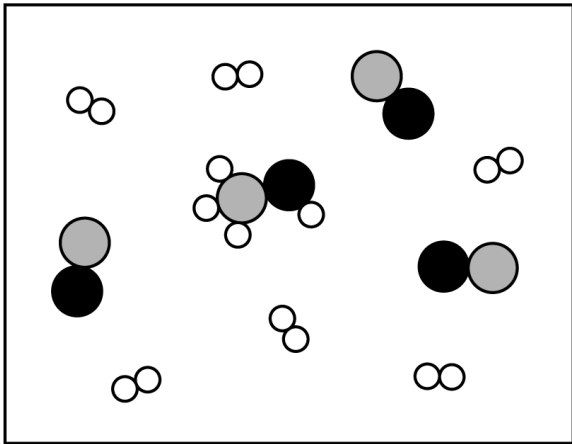
2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

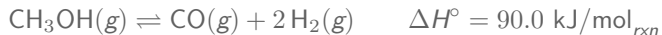
(a) Are the hydrogen atoms oxidized or are they reduced in the forward reaction? Justify your answer in terms of oxidation numbers.

Question 2



Question 2

2022 ■ Q2



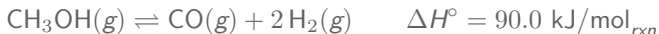
Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(b) In the following box, draw the complete Lewis electron-dot diagram for the carbon monoxide molecule in which every atom obeys the octet rule. Show all bonding and nonbonding valence electrons.

[A blank box is provided containing the unconnected atomic symbols “C” and “O”, for the student to complete into a full Lewis structure.]

Question 2

2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(c)(i) The values of the standard molar entropies of the compounds involved in the reaction are given in the following table.

Substance	S° (J/(K · mol))	CH ₃ OH(<i>g</i>)	240.	CO(<i>g</i>)	198	H ₂ (<i>g</i>)
			131			

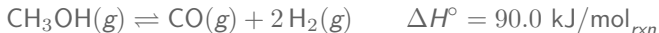
Use the data in the table to calculate the value of the standard entropy change, ΔS° , in J/(K · mol_{rxn}), for the reaction.

Question 2

(c)(ii) Calculate the value of ΔG° , in $\text{kJ/mol}_{\text{rxn}}$, for the reaction at 375 K. Assume that ΔH° and ΔS° are independent of temperature.

Question 2

2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(d) The following particle-level diagram shows a representative sample of the equilibrium mixture represented by the equation given.

[A rectangular box (the "container") contains a mixture of particles at equilibrium: several two-linked-open-circle pairs (H₂), and several three-part particles each made of one gray sphere + one black sphere + one small open circle (CO), plus one larger cluster shown as CH₃OH. A key box beside it identifies: a cluster of one gray sphere +

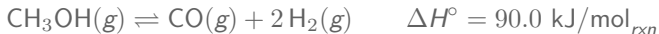
Question 2

one black sphere + three small open circles = CH_3OH ; one gray sphere + one black sphere = CO ; two small open circles joined = H_2 . Counting the container: there appear to be 1 CH_3OH particle, 4 CO particles, and 8 H_2 particles.]

Use information from the particle diagram to calculate the partial pressure of CO at equilibrium when the total pressure of the equilibrium mixture is 12.0 atm.

Question 2

2022 ■ Q2

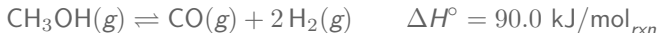


Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(e) Write the expression for the equilibrium constant, K_p , for the reaction.

Question 2

2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(f)



The reaction system represented by the equation is allowed to achieve equilibrium at a different temperature. The following table gives the partial pressure of each species in the equilibrium mixture.

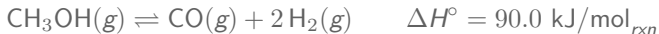
Question 2

Substance	Partial Pressure at Different Temperature		CH ₃ OH(<i>g</i>)	2.7 atm
CO(<i>g</i>)	4.2 atm	H ₂ (<i>g</i>)	8.4 atm	

Use the information in the table to calculate the value of the equilibrium constant, K_p , at the new temperature.

Question 2

2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(g) The volume of the container is rapidly doubled with no change in temperature. As equilibrium is re-established, does the number of moles of $\text{CH}_3\text{OH}(g)$ increase, decrease, or remain the same? Justify your answer by comparing the value of the reaction quotient, Q , with the value of the equilibrium constant, K_p .

Solution 2

(a)

Mark scheme

- The H atoms are reduced because they change from an oxidation number of +1 (in CH_3OH) to 0 (in H_2) in the forward reaction.

Solution 2

(b)

Mark scheme

- Complete Lewis electron-dot diagram for CO obeying the octet rule: a carbon–oxygen triple bond ($\text{:C}\equiv\text{O:}$) with one lone pair on carbon and one lone pair on oxygen, giving each atom an octet (triple bond = 6 shared electrons + 1 lone pair = 8 electrons around each atom).

Solution 2

(c)(i)

Mark scheme

- $\Delta S^{\circ}_{\text{rxn}} = \Sigma \Delta S^{\circ}_{\text{products}} - \Sigma \Delta S^{\circ}_{\text{reactants}} = (\Delta S^{\circ}_{\text{CO(g)}} + 2\Delta S^{\circ}_{\text{H}_2\text{(g)}}) - \Delta S^{\circ}_{\text{CH}_3\text{OH(g)}}$ (1 point for correct stoichiometry, may be implicit). Using the table values (S° : $\text{CH}_3\text{OH(g)} = 240. \text{ J/(K} \cdot \text{mol)}$, $\text{CO(g)} = 198 \text{ J/(K} \cdot \text{mol)}$, $\text{H}_2\text{(g)} = 131 \text{ J/(K} \cdot \text{mol)}$): $\Delta S^{\circ}_{\text{rxn}} = 198 + 2(131) - 240. = 220. \text{ J/(K} \cdot \text{mol}_{\text{rxn}})$ (1 point for the correct calculated value).

Solution 2

(c)(ii)

Mark scheme

- $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ = 90.0 \text{ kJ/mol}_{\text{rxn}} - (375 \text{ K})(0.220 \text{ kJ/(K} \cdot \text{mol}_{\text{rxn}})) = +7.5 \text{ kJ/mol}_{\text{rxn}}$ (assuming ΔH° and ΔS° are independent of temperature).

Solution 2

(d)

Mark scheme

- From the particle-level diagram, CO particles make up 3 of the 10 total gas particles shown in the container. With a total pressure of 12.0 atm: $P_{\text{CO}} = (3/10)(12.0 \text{ atm}) = 3.6 \text{ atm}$.

Solution 2

(e)

Mark scheme

- $K_p = (P_{\text{CO}})(P_{\text{H}_2})^2 / (P_{\text{CH}_3\text{OH}})$.

Solution 2

(f)

Mark scheme

- Using the partial pressures at the new equilibrium temperature ($\text{CH}_3\text{OH} = 2.7$ atm, $\text{CO} = 4.2$ atm, $\text{H}_2 = 8.4$ atm): $K_p = (P_{\text{CO}})(P_{\text{H}_2})^2 / (P_{\text{CH}_3\text{OH}}) = (4.2)(8.4)^2 / (2.7) = 110$.

Solution 2

(g) Mark scheme

- Comparison of Q and K (1 point): doubling the container volume causes the partial pressure of each species to decrease by a factor of two; because there are more moles of gaseous products than reactants, the resulting decrease in the numerator of Q is larger (raised to a higher net power) than the decrease in the denominator, making $Q_p < K_p$ — explicitly $Q_p = [(P_{\text{CO}}/2)(P_{\text{H}_2}/2)^2] / (P_{\text{CH}_3\text{OH}}/2) = K_p/4 \approx 27 < K_p$. Answer and justification (1 point): the number of moles of $\text{CH}_3\text{OH}(\text{g})$ will decrease. Since $Q_p < K_p$, the reaction proceeds forward as equilibrium re-establishes, increasing the partial pressures (moles) of the products and decreasing the moles of CH_3OH .

Question 2

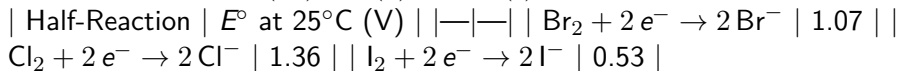
2019 ■ Q2

Answer the following questions relating to the chemistry of the halogens.

(a) The molecular formulas of diatomic bromine, chlorine, fluorine, and iodine are written below. Circle the formula of the molecule that has the longest bond length. Justify your choice in terms of atomic structure.



A chemistry teacher wants to prepare Br_2 . The teacher has access to the following three reagents: NaBr(aq) , $\text{Cl}_2(\text{g})$, and $\text{I}_2(\text{s})$.



Question 2

Half-Reaction	E° at 25°C (V)
$\text{Br}_2 + 2 e^- \rightarrow 2 \text{Br}^-$	1.07
$\text{Cl}_2 + 2 e^- \rightarrow 2 \text{Cl}^-$	1.36
$\text{I}_2 + 2 e^- \rightarrow 2 \text{I}^-$	0.53

Question 2

Bond	Bond Energy (kJ/mol)
Br – Br	193
Cl – Cl	243
Br – Cl	?

Question 2

2019 ■ Q2

Answer the following questions relating to the chemistry of the halogens.

(b) Using the data in the table above, write the balanced equation for the thermodynamically favorable reaction that will produce Br_2 when the teacher combines two of the reagents. Justify that the reaction is thermodynamically favorable by calculating the value of E° for the reaction.

Br_2 and Cl_2 can react to form the compound BrCl .

Question 2

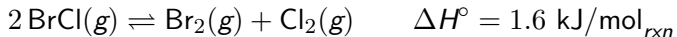
2019 ■ Q2

Answer the following questions relating to the chemistry of the halogens.

(c) The boiling point of Br_2 is 332 K, whereas the boiling point of BrCl is 278 K.

Explain this difference in boiling point in terms of all the intermolecular forces present between molecules of each substance.

The compound BrCl can decompose into Br_2 and Cl_2 , as represented by the balanced chemical equation below.



A 0.100 mole sample of pure $\text{BrCl}(g)$ is placed in a previously evacuated, rigid 2.00 L container at 298 K. Eventually the system reaches equilibrium according to the equation above.

Question 2

2019 ■ Q2

Answer the following questions relating to the chemistry of the halogens.

(d) Calculate the pressure in the container before equilibrium is established.

Question 2

2019 ■ Q2

Answer the following questions relating to the chemistry of the halogens.

(e) Write the expression for the equilibrium constant, K_{eq} , for the decomposition of BrCl .

After the system has reached equilibrium, 42 percent of the original BrCl sample has decomposed.

Question 2

2019 ■ Q2

Answer the following questions relating to the chemistry of the halogens.

(f) Determine the value of K_{eq} for the decomposition reaction of BrCl at 298 K.

Question 2

2019 ■ Q2

Answer the following questions relating to the chemistry of the halogens.

(g) Calculate the bond energy of the Br-Cl bond, in kJ/mol, using ΔH° for the reaction (1.6 kJ/mol_{rxn}) and the information in the following table.

Bond	Bond Energy (kJ/mol)
Br - Br	193
Cl - Cl	243
Br - Cl	?

Solution 2

(a)

Mark scheme

- I₂ (circled). I₂ has the longest bond length because the atomic radius of I is greater than the radii of the other halogen atoms (Br, Cl, F), so the internuclear distance between the two bonded I atoms is greater than in the other diatomic halogens. 1 point for circling I₂ with a valid atomic-structure justification.

Solution 2

(b)

Mark scheme

- Balanced equation (Cl_2 is a strong enough oxidizer to oxidize Br since $E^\circ(\text{Cl}_2/\text{Cl}^-) = 1.36 \text{ V} > E^\circ(\text{Br}_2/\text{Br}^-) = 1.07 \text{ V}$, whereas I_2 cannot): $2 \text{Br}(\text{aq}) + \text{Cl}_2(\text{g}) \rightarrow \text{Br}_2 + 2 \text{Cl}(\text{aq})$. 1 point for the correct balanced equation. $E^\circ = E^\circ(\text{reduced species}) - E^\circ(\text{oxidized species}) = 1.36 \text{ V} - 1.07 \text{ V} = +0.29 \text{ V}$; a positive E° confirms the reaction is thermodynamically favorable. 1 point for the correct E° calculation.

Solution 2

(c)

Mark scheme

- Br₂(l) has only London dispersion forces between its nonpolar molecules. BrCl(l) is polar, so it has both London forces and dipole-dipole forces. 1 point for correctly identifying the IMFs present in each substance. However, Br₂ has a larger, more polarizable electron cloud than BrCl, so the London forces in Br₂(l) are stronger than the combined (London + dipole-dipole) forces in BrCl(l); this is why Br₂'s boiling point (332 K) is higher than BrCl's (278 K) despite BrCl being polar. 1 point for this valid explanation invoking polarizability.

Solution 2

(d)

Mark scheme

- $P = nRT/V = (0.100 \text{ mol})(0.08206 \text{ L} \cdot \text{atm} \cdot \text{mol}^{-1} \cdot \text{K}^{-1})(298 \text{ K}) / (2.00 \text{ L})$
 $= 1.22 \text{ atm}$. 1 point for the correct pressure with consistent units.

Solution 2

(e)

Mark scheme

- $K_{eq} = [\text{Br}_2][\text{Cl}_2] / [\text{BrCl}]^2$ (equivalently, in terms of partial pressures: $K_{eq} = P(\text{Br}_2) \cdot P(\text{Cl}_2) / P(\text{BrCl})^2$). 1 point for a correct equilibrium expression.

Solution 2

(f)

Mark scheme

- ICE table (partial pressures, atm) for $2 \text{ BrCl(g)} \rightleftharpoons \text{Br}_2\text{(g)} + \text{Cl}_2\text{(g)}$: Initial 1.22, 0, 0; Change $-2x$, $+x$, $+x$; Equilibrium 0.71, 0.26, 0.26. Since 42% of BrCl decomposed, $P(\text{BrCl decomposed}) = (0.42)(1.22 \text{ atm}) = 0.51 \text{ atm} = 2x$, so $x = 0.26 \text{ atm}$. 1 point for the correct stoichiometric (ICE) values at equilibrium. $K_{\text{eq}} = (0.26)(0.26)/(0.71)^2 = 0.13$. 1 point for a K_{eq} value consistent with the student's ICE table (a molar-concentration-based solution also earns full credit).

Solution 2

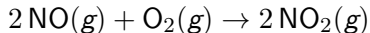
(g)

Mark scheme

- $\Delta H^\circ = \Sigma(\text{bond energies})_{\text{broken}} - \Sigma(\text{bond energies})_{\text{formed}}$. $1.6 \text{ kJ/mol} = 2(\text{Br-Cl bond energy}) - (193 \text{ kJ/mol} + 243 \text{ kJ/mol})$; $(436 + 1.6) \text{ kJ/mol} = 2(\text{Br-Cl bond energy})$; Br-Cl bond energy = 219 kJ/mol . 1 point for the correct calculation.

Question 2

2018 ■ Q2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

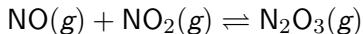
(a) The particle-level representation of the equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in the flask at the completion of the reaction between $\text{NO}(g)$ and $\text{O}_2(g)$ is shown below in the box on the right. In the box below on the left, draw the particle-level representation of the reactant mixture of $\text{NO}(g)$ and $\text{O}_2(g)$ 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 NO₂ molecules (each one filled circle bonded to two open circles), scattered randomly in the box.]

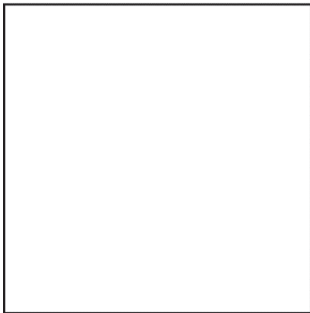
The student reads in a reference text that $\text{NO}(g)$ and $\text{NO}_2(g)$ will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.



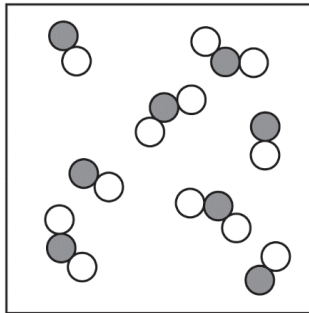
ΔH_{298}°	ΔS_{298}°	ΔG_{298}°	— — —	$-40.4 \text{ kJ/mol}_{rxn}$	$-138.5 \text{ J/(K} \cdot \text{mol}_{rxn})$	0.87
kJ/mol _{rxn}						

Question 2

Oxygen atom =  Nitrogen atom = 

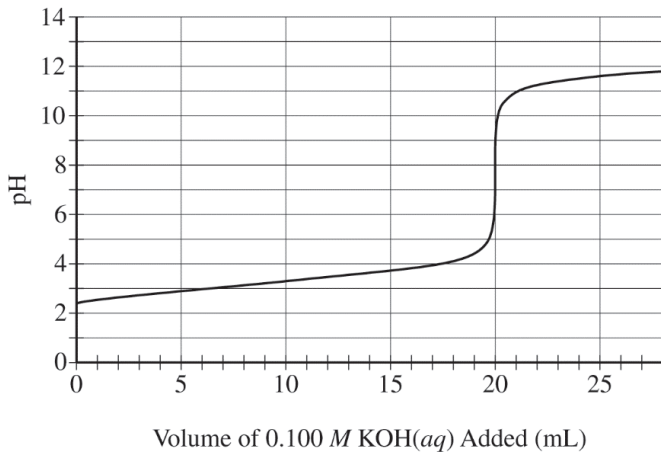


Reactant Mixture

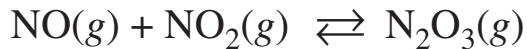


Product Mixture

Question 2



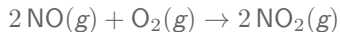
Question 2



ΔH_{298}°	ΔS_{298}°	ΔG_{298}°
$-40.4 \text{ kJ/mol}_{rxn}$	$-138.5 \text{ J/(K} \cdot \text{mol}_{rxn})$	$0.87 \text{ kJ/mol}_{rxn}$

Question 2

2018 ■ Q2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

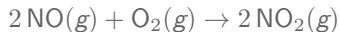
(b)(i) The student begins with an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

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 $P_{\text{N}_2\text{O}_3}$ at equilibrium be equal to 1.0 atm? Justify your answer.

Question 2

2018 ■ Q2

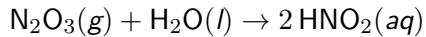


A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

(c) The student hypothesizes that increasing the temperature will increase the amount of $\text{N}_2\text{O}_3(g)$ in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

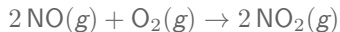
$\text{N}_2\text{O}_3(g)$ reacts with water to form nitrous acid, $\text{HNO}_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.

Question 2



Question 2

2018 ■ Q2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, 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.

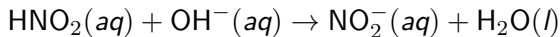
[Box showing the skeletal structure: H O N O, written left to right in a line.]

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 $\text{N}_2\text{O}_3(g)$ into distilled water. Assume that the reaction goes to completion and that HNO_2 is the only species produced. To determine the concentration of $\text{HNO}_2(aq)$ in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 M $\text{KOH}(aq)$. The neutralization reaction is represented below.



The following titration curve shows the change in pH of the solution during the titration.

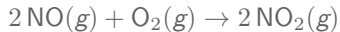
[Titration curve graph: Y-axis pH from 0 to 14 in increments of 2. X-axis "Volume of 0.100 M $\text{KOH}(aq)$ Added (mL)" from 0 to 25+ in increments of 5. The curve starts around pH 2.3 at 0 mL, rises very gradually and slightly through a small buffer region

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



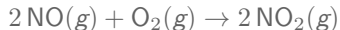
A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

(e)(i) Use the titration curve and the information above to determine the initial concentration of the $\text{HNO}_2(aq)$ solution.

(e)(ii) Use the titration curve and the information above to estimate the value of $\text{p}K_a$ for $\text{HNO}_2(aq)$.

Question 2

2018 ■ Q2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

(f) During the titration, after a volume of 15 mL of 0.100 *M* $\text{KOH}(aq)$ has been added, which species, $\text{HNO}_2(aq)$ or $\text{NO}_2^-(aq)$, 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 $2 \text{NO(g)} + \text{O}_2\text{(g)} \rightarrow 2 \text{NO}_2\text{(g)}$ 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

- $\Delta G = -RT \ln K$, so $K = e^{(-\Delta G/RT)} = e^{[-870 \text{ J/mol} / ((8.314 \text{ J/(mol K)})(298 \text{ K}))]} = e^{-0.351} = 0.70$. 1 point is earned for the correct calculation of K .

Solution 2

(b)(ii)

Mark scheme

- No, $P(\text{N}_2\text{O}_3)$ will not equal 1.0 atm at equilibrium. $P(\text{N}_2\text{O}_3)$ 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 NO_2) will remain at equilibrium, so $P(\text{N}_2\text{O}_3)$ 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 $\text{NO(g)} + \text{NO}_2\text{(g)} \rightleftharpoons \text{N}_2\text{O}_3\text{(g)}$ is exothermic ($\Delta H_{298} = -40.4 \text{ kJ/mol}_{\text{rxn}}$), increasing the temperature will favor the formation of the reactants (shift left), according to Le Chatelier's principle, so the amount of $\text{N}_2\text{O}_3\text{(g)}$ 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 HNO_2 (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 sp^2 hybridized (it is bonded to 2 O atoms and has 1 lone pair, i.e., 3 electron domains, giving trigonal planar / sp^2 geometry). 1 point is earned for the correct answer, sp^2 .

Solution 2

(e)(i)

Mark scheme

- At the equivalence point (from the titration curve), 20. mL of 0.100 M KOH has been added: $20. \text{ mL} \times 0.100 \text{ mol KOH}/1000 \text{ mL} = 0.0020 \text{ mol KOH}$ added, which equals 0.0020 mol HNO₂ originally present (1:1 stoichiometry of $\text{HNO}_2 + \text{OH}^- \rightarrow \text{NO}_2^- + \text{H}_2\text{O}$). Initial concentration = $0.0020 \text{ mol HNO}_2 / 0.100 \text{ L} = 0.020 \text{ M HNO}_2$. 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 $\text{pH} = \text{pKa}$. 1 point is earned for an acceptable estimate of pKa (values near 3.4 accepted).

Solution 2

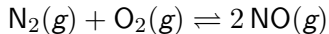
(f)

Mark scheme

- $\text{NO}_2\text{-(aq)}$ 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 (NO_2^-) than the acid (HNO_2) is present. 1 point is earned for the correct choice AND a valid justification.

Question 3

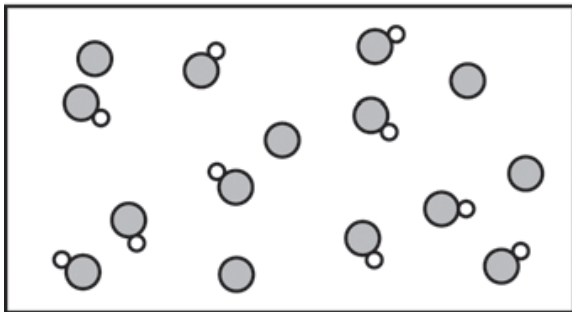
2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(a) Write the expression for the equilibrium constant, K_p , for the forward reaction.

Question 3



Question 3

2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(b) A student injects $\text{N}_2(g)$ and $\text{O}_2(g)$ into a previously evacuated, rigid vessel and raises the temperature of the vessel to 2000°C . At this temperature the initial partial pressures of $\text{N}_2(g)$ and $\text{O}_2(g)$ are 6.01 atm and 1.61 atm, respectively. The system is allowed to reach equilibrium. The partial pressure of $\text{NO}(g)$ at equilibrium is 0.122 atm. Calculate the value of K_p .

Question 3

2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(c)(i) Nitrogen monoxide, $\text{NO}(g)$, can undergo further reactions to produce acids such as HNO_2 , a weak acid with a K_a of 4.0×10^{-4} and a $\text{p}K_a$ of 3.40.

A student is asked to make a buffer solution with a pH of 3.40 by using 0.100 M $\text{HNO}_2(aq)$ and 0.100 M $\text{NaOH}(aq)$.

Explain why the addition of 0.100 M $\text{NaOH}(aq)$ to 0.100 M $\text{HNO}_2(aq)$ can result in the formation of a buffer solution. Include the net ionic equation for the reaction that occurs when the student adds the $\text{NaOH}(aq)$ to the $\text{HNO}_2(aq)$.

Question 3

(c)(ii) Determine the volume, in mL, of $0.100\text{ M NaOH}(aq)$ the student should add to $100.\text{ mL}$ of $0.100\text{ M HNO}_2(aq)$ to make a buffer solution with a pH of 3.40. Justify your answer.

Question 3

2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(d) A second student makes a buffer by dissolving 0.100 mol of $\text{NaNO}_2(s)$ in 100. mL of 1.00 M $\text{HNO}_2(aq)$. Which is more resistant to changes in pH when a strong acid or a strong base is added, the buffer made by the second student or the buffer made by the first student in part (c) ? Justify your answer.

Question 3

2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(e) A new buffer is made using $\text{HNO}_2(aq)$ as one of the ingredients. A particulate representation of a small representative portion of the buffer solution is shown below. (Cations and water molecules are not shown.) Is the pH of the buffer represented in the diagram greater than, less than, or equal to 3.40 ? Justify your answer.
[Diagram: a rectangular box containing a scattered arrangement of small circles representing particles, with a legend above showing two symbol types: "HNO₂ molecule" (drawn as two overlapping circles) and "NO₂⁻ ion" (drawn as a single circle).]

Question 3

The box shows a mixture of both symbol types scattered throughout, with noticeably more HNO_2 -molecule symbols (two-circle pairs) than NO_2^- -ion symbols (single circles) — approximately 8 paired (HNO_2) symbols and 4 single (NO_2^-) symbols visible.]

Solution 3

(a)

Mark scheme

- $K_p = (P_{\text{NO}})^2 / [(P_{\text{N}_2})(P_{\text{O}_2})]$. 1 point earned for a correct K_p expression.

Solution 3

(b)

Mark scheme

- ICE table (atm): Initial $\text{N}_2 = 6.01$, $\text{O}_2 = 1.61$, $\text{NO} = 0$; Change $-x$, $-x$, $+2x$; Equilibrium $6.01-x$, $1.61-x$, 0.122 . Since $2x = 0.122$ atm, $x = 0.0610$ atm, so at equilibrium $P_{\text{N}_2} = 5.95$ atm and $P_{\text{O}_2} = 1.55$ atm. $K_p = (0.122)^2 / [(5.95)(1.55)] = 0.00161$. 1 point earned for the correct equilibrium partial pressures of reactants and products (may be implicit); 1 point earned for the correct calculation of K_p .

Solution 3

(c)(i)

Mark scheme

- NaOH will neutralize some of the HNO₂ to produce NO₂⁻. The resulting solution contains a mixture of a weak acid (HNO₂) and its conjugate base (NO₂⁻), which is a buffer solution. Net ionic equation: $\text{HNO}_2 + \text{OH}^- \rightarrow \text{NO}_2^- + \text{H}_2\text{O}$. 1 point earned for the recognition that the solution produced is a mixture of a weak acid and its conjugate base; 1 point earned for the correct net ionic equation.

Solution 3

(c)(ii)

Mark scheme

- The student should add 50.0 mL of 0.100 M NaOH(aq). Using the Henderson-Hasselbalch equation, $\text{pH} = \text{pK}_a + \log([\text{NO}_2^-]/[\text{HNO}_2])$, so $\text{pH} = \text{pK}_a$ exactly when $[\text{HNO}_2] = [\text{NO}_2^-]$; since the target pH (3.40) equals pK_a , a 1-to-1 ratio of HNO₂ to NO₂⁻ is required, i.e. half of the 10.0 mmol HNO₂ (100. mL × 0.100 M) must be converted, which needs 5.00 mmol NaOH = 50.0 mL of 0.100 M NaOH. 1 point earned for the correct volume; 1 point earned for clearly indicating a 1-to-1 ratio of HNO₂ and NO₂⁻ is required (calculation not required for this point).

Solution 3

(d)

Mark scheme

- The buffer made by the second student (0.100 mol NaNO_2 dissolved in 100. mL of 1.00 M HNO_2) is more resistant to changes in pH, because it contains a higher concentration of HNO_2 and NO_2^- available to react with added H^+ or OH^- ions (greater buffer capacity) than the buffer from part (c). 1 point earned for the correct choice and a valid justification.

Solution 3

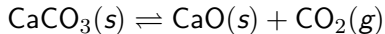
(e)

Mark scheme

- The pH of the solution is less than 3.40. If $[\text{HNO}_2] = [\text{NO}_2^-]$, $\text{pH} = \text{pK}_a$ and the pH of the solution would be 3.40; since the particulate diagram shows more HNO_2 molecules than NO_2^- ions (i.e. $[\text{HNO}_2] > [\text{NO}_2^-]$), the solution has a pH less than 3.40 (equivalently, with the diagram's ratio of about 5 NO_2^- to 10 HNO_2 , $\text{pH} = 3.40 + \log(5/10) = 3.10$). 1 point earned for the correct choice; 1 point earned for a valid justification.

Question 4

2014 ■ Q4



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 $\text{CaCO}_3(s)$ 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 $\text{CO}_2(g)$ 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 $\text{CaCO}_3(s)$. In this experiment, the final pressure in the container was 1.04 atm, which was the same final pressure as in the first experiment.

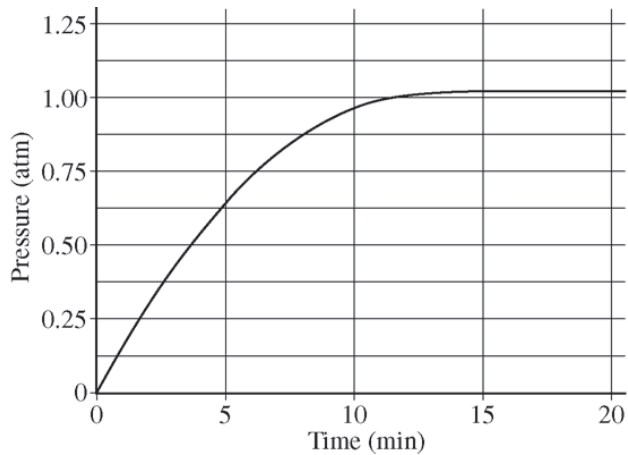
- (a)** Calculate the number of moles of $\text{CO}_2(g)$ present in the container after 20 minutes of heating.
- (b)** The student claimed that the final pressure in the container in each experiment became constant because all of the $\text{CaCO}_3(s)$ had decomposed. Based on the data in the experiments, do you agree with this claim? Explain.

Question 4

(c) After 20 minutes some $\text{CO}_2(g)$ 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 $\text{CaCO}_3(s)$ at 1100 K? Justify your answer.

Question 4



Solution 4

(a)

Mark scheme

- Using the ideal gas law:

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

Solution 4

(b)

Mark scheme

- Do not agree with the claim. In experiment 1, moles of $\text{CaCO}_3 = 50.0 \text{ g} / 100.09 \text{ g/mol} = 0.500 \text{ mol CaCO}_3$; if the reaction had gone to completion, 0.500 mol of CO_2 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 CaCO_3) both reached the same constant final pressure of 1.04 atm; since adding more reactant did not produce more product, not all of the CaCO_3 could have reacted — an equilibrium condition was reached instead, with some solid CaCO_3 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 CO_2 pressure of 1.04 atm. Raising the pressure to 1.5 atm shifts the reaction toward the reactant (Le Chatelier's principle), and $\text{CO}_2(\text{g})$ 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, $K_p = P_{\text{CO}_2} = 1.04$. (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 K_p cannot be calculated from the data.)