Past-paper walk-through

Hess's Law ▪ 6.9

eXercise

Questions in this set

- 2026 Q7
- 2025 Q3
- 2023 Q2
- 2019 Q2
- 2015 Q7
- 2014 Q6

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 7

2026 ▪ Q7

The following information applies to parts A and B.
Sodium metal reacts with oxygen gas according to Equation 1.

$$\text{Equation 1: } 4\,\mathrm{Na}(s) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{Na_2O}(s) \qquad \Delta H^\circ{}_{rxn} = -828\ \mathrm{kJ/mol}_{rxn}$$

Standard enthalpies of formation are provided in Table 1.

Substance	$\Delta H^\circ{}_f$ (kJ/mol)
$\mathrm{Na}(s)$	0
$\mathrm{O_2}(g)$	0
$\mathrm{Na_2O}(s)$	?

(a) Based on the information given, **calculate** the value of $\Delta H^\circ{}_f$ for $\mathrm{Na_2O}(s)$. Show the work that leads to your answer.

(b) An 18.4 g sample of $\mathrm{Na}(s)$ reacts with 12.8 g of $\mathrm{O_2}(g)$ according to Equation 1. **Calculate** the total amount of heat, in kilojoules, released during this process. Show the work that leads to your answer.

Question 7

(c) Lattice enthalpy can be defined as the energy required to separate an ionic crystal into gaseous ions. $Rb_2O(s)$ and $Na_2O(s)$ have similar crystal structures, and their lattice enthalpies are given in Table 2.

Compound	Lattice Enthalpy (kJ/mol)
$Na_2O(s)$	2481
$Rb_2O(s)$	2163

Using Coulomb's law, **explain** why the lattice enthalpy of $Rb_2O(s)$ is smaller than that of $Na_2O(s)$.

Table 2

Compound	Lattice Enthalpy (kJ/mol)
$Na_2O\,(s)$	2481
$Rb_2O\,(s)$	2163

Question 7

Table 1

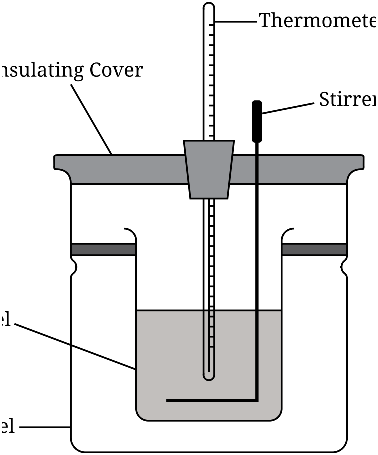
Substance	ΔH_f° (kJ/mol)
$Na\,(s)$	0
$O_2\,(g)$	0
$Na_2O\,(s)$	?

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 P4 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.

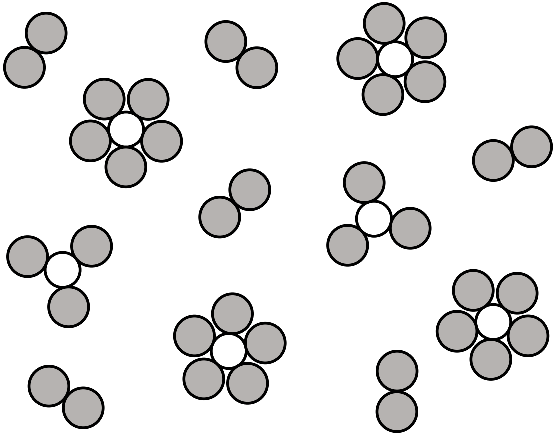
Question 3



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	$4.18\ \mathrm{J/(g{\cdot}°C)}$

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 P4 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.

Equation 1: $P_4(s) + 5\,O_2(g) \rightarrow P_4O_{10}(s)$

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 P4 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.

Equation 2: $P_4O_{10}(s) + 6\,H_2O(l) \rightarrow 4\,H_3PO_4(aq)$

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/$(g \cdot° C)$ |
(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 P4 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.

$P_4(s)$ also reacts readily with $Cl_2(g)$ to produce phosphorus trichloride, $PCl_3(g)$, which in turn reacts with $Cl_2(g)$ in an equilibrium process to produce $PCl_5(g)$. The reactions are represented by equations 3 and 4.

Equation 3: $P_4(s) + 6\,Cl_2(g) \rightarrow 4\,PCl_3(g)$ $\quad \Delta H_1^\circ = -1148$ kJ/mol$_{rxn}$

Equation 4: $PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$ $\quad \Delta H_2^\circ = -88$ kJ/mol$_{rxn}$

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 P4 skeleton, with no lone pairs drawn yet.]

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

Equation 5: $\frac{1}{4}P_4(s) + \frac{5}{2}Cl_2(g) \rightarrow PCl_5(g) \qquad \Delta H_f^\circ = ?$

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.
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[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 P4 skeleton, with no lone pairs drawn yet.]

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

Equation 4: $\mathrm{PCl_3}(g) + \mathrm{Cl_2}(g) \rightleftharpoons \mathrm{PCl_5}(g) \qquad \Delta H_2^\circ = -88\ \mathrm{kJ/mol}_{rxn}$

(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 ($P_4(s) + 5\,O_2(g) \rightarrow P_4O_{10}(s)$), 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 $\Delta G^\circ_{rxn} = \Delta H^\circ_{rxn} - T\Delta S^\circ_{rxn}$, the reaction must have $\Delta G^\circ_{rxn} < 0$ to be favorable. Because the reaction is exothermic, $\Delta H^\circ_{rxn} < 0$ and enthalpy contributes to favorability. $\Delta S^\circ_{rxn} < 0$, 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 $P_4O_{10}(s)$ with water (equation 2: $P_4O_{10}(s) + 6\,H_2O(l) \rightarrow 4\,H_3PO_4(aq)$) that parts (i) and (ii) below use.

Solution 3

(c)(i)

Mark scheme

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

Solution 3

(c)(ii)

Mark scheme

- $q_{rxn} = -q_{surr} = -0.16$ kJ.
  $$\Delta H^{\circ}_{rxn} = \frac{-0.16 \text{ kJ}}{0.100 \text{ g } P_4O_{10}} \times \frac{283.9 \text{ g } P_4O_{10}}{1 \text{ mol } P_4O_{10}} \times \frac{1 \text{ mol } P_4O_{10}}{1 \text{ mol}_{rxn}} = -450 \text{ kJ/mol}_{rxn}.$$
  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:
$$\Delta H^{\circ}_{f,\mathrm{PCl}_5(g)} = \frac{1}{4}\Delta H^{\circ}_1 + \Delta H^{\circ}_2 = \frac{1}{4}(-1148) + (-88) = -375 \text{ kJ/mol}.$$

Solution 3

(f)

Mark scheme

- No separate response required — this is the context/stem presenting equation 4 ($PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$, $\Delta H_2^\circ = -88$ kJ/mol$_{rxn}$) 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): $K_p = \dfrac{P_{PCl_5}}{(P_{PCl_3})(P_{Cl_2})} = \dfrac{4.00}{(2.00)(6.00)} = \dfrac{1}{3} = 0.333$.

Solution 3

(f)(ii)

Mark scheme

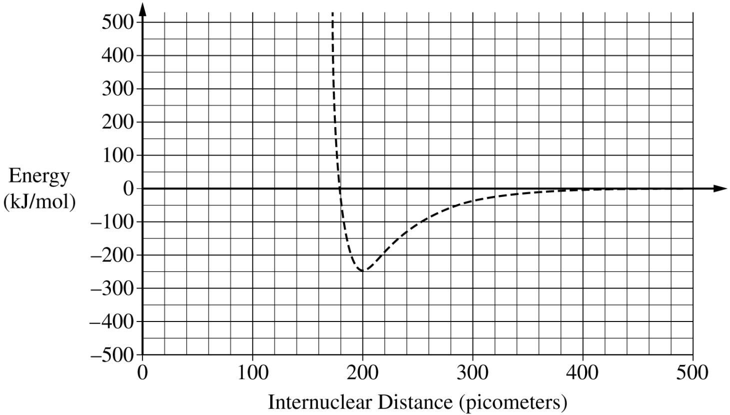
- Decrease. The negative value of ΔH_2° indicates the reaction is exothermic. Because exothermic reactions favor reactant formation at higher temperature (the equilibrium shifts toward reactants as heat is added), the value of K_p decreases.

Question 2

2023 ▪ Q2

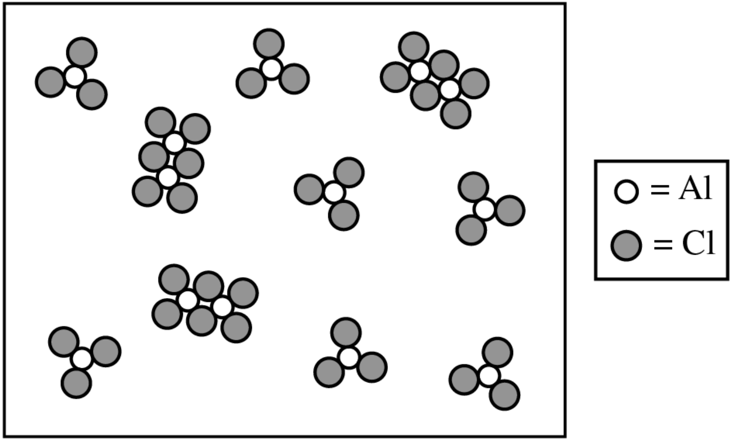
In the gas phase, $AlCl_3$ is a molecular substance. A reaction of gaseous $AlCl_3$ at high temperature is represented by the following balanced equation.
Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$
(a) How many grams of $Cl(g)$ can be formed from 1.25 mol of $AlCl_3(g)$?

Question 2



ɔn the graph, what is the bond length, in picometers, for Cl_2 ? __________

Question 2



Question 2

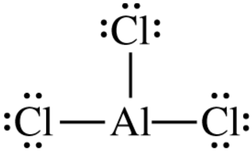


Diagram 1

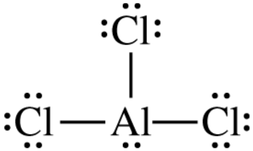


Diagram 2

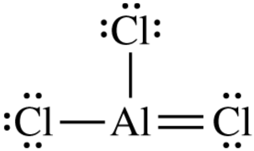


Diagram 3

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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

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

Reaction Number	Equation	ΔH°_{rxn} (kJ/mol$_{rxn}$)
2	$Al(s) + \frac{3}{2}Cl_2(g) \rightarrow AlCl_3(g)$	-583
3	$Al(s) \rightarrow Al(g)$	$+326$
4	$Cl_2(g) \rightarrow 2\,Cl(g)$	$+243$

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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(d)(i) Three proposed Lewis diagrams for the $AlCl_3(g)$ 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) — Cl=Al on the right side.]
Diagram 1, Diagram 2, Diagram 3 (labeled beneath each structure).

Question 2

The $AlCl_3(g)$ 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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

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

$$2\,AlCl_3(g) \rightleftharpoons Al_2Cl_6(g)$$

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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(f) A particle-level diagram of an equilibrium mixture of $AlCl_3(g)$ and $Al_2Cl_6(g)$ 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

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

Solution 2

(b) Mark scheme

- Apply Hess's law using reactions 2, 3, and 4: reverse reaction 2 ($AlCl_3(g) \rightarrow Al(s) + \frac{3}{2}Cl_2(g)$, $\Delta H = -(-583) = +583$ kJ/mol$_{rxn}$) and multiply reaction 4 by $\frac{3}{2}$ ($\frac{3}{2}Cl_2(g) \rightarrow 3\,Cl(g)$, $\Delta H = 1.5(+243) = +365$ kJ/mol$_{rxn}$), then add reaction 3 unchanged: $\Delta H_1^\circ = -\Delta H_2^\circ + \Delta H_3^\circ + 1.5(\Delta H_4^\circ) = -(-583) + 326 + 1.5(243) = 1274$ kJ/mol$_{rxn}$.

Solution 2

(c)(i)

Mark scheme

- Bond length $\approx$ 200 picometers ($\pm$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 $AlCl_3$(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

- $K_p = \dfrac{P_{\mathrm{Al_2Cl_6}}}{\left(P_{\mathrm{AlCl_3}}\right)^2}$.

Solution 2

(f) Mark scheme

- Using mole fractions read from the particle diagram ($\chi_{\mathsf{AlCl_3}} = \frac{7}{10}$, $\chi_{\mathsf{Al_2Cl_6}} = \frac{3}{10}$) and total pressure 22.1 atm: $K_p = \dfrac{\chi_{\mathsf{Al_2Cl_6}}(P_{total})}{(\chi_{\mathsf{AlCl_3}}(P_{total}))^2} = \dfrac{\frac{3}{10}(22.1)}{(\frac{7}{10}(22.1))^2} = 0.0277.$

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.

$$Br_2 \qquad Cl_2 \qquad F_2 \qquad I_2$$

A chemistry teacher wants to prepare Br_2. The teacher has access to the following three reagents: $NaBr(aq)$, $Cl_2(g)$, and $I_2(s)$.
| Half-Reaction | E° at 25°C (V) | |—|—| | $Br_2 + 2\,e^- \rightarrow 2\,Br^-$ | 1.07 | |
$Cl_2 + 2\,e^- \rightarrow 2\,Cl^-$ | 1.36 | | $I_2 + 2\,e^- \rightarrow 2\,I^-$ | 0.53 |

Question 2

Half-Reaction	$E°$ at 25°C (V)
$Br_2 + 2\,e^- \rightarrow 2\,Br^-$	1.07
$Cl_2 + 2\,e^- \rightarrow 2\,Cl^-$	1.36
$I_2 + 2\,e^- \rightarrow 2\,I^-$	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.

$$2\,\mathrm{BrCl}(g) \rightleftharpoons \mathrm{Br_2}(g) + \mathrm{Cl_2}(g) \qquad \Delta H^\circ = 1.6\ \mathrm{kJ/mol}_{rxn}$$

A 0.100 mole sample of pure 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 $E°(Cl_2/Cl^-)=1.36$ V > $E°(Br_2/Br^-)=1.07$ V, whereas I_2 cannot): $2\,Br^-(aq) + Cl_2(g) \rightarrow Br_2 + 2\,Cl^-(aq)$. 1 point for the correct balanced equation. $E° = E°(\text{reduced species}) - E°(\text{oxidized species}) = 1.36\text{ V} - 1.07\text{ V} = +0.29$ 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

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

Solution 2

(e)

Mark scheme

- Keq = [Br2][Cl2] / $[BrCl]^2$ (equivalently, in terms of partial pressures: Keq = P(Br2) · P(Cl2) / $P(BrCl)^2$). 1 point for a correct equilibrium expression.

Solution 2

(f)

Mark scheme

- ICE table (partial pressures, atm) for 2 BrCl(g)   Br2(g) + Cl2(g): Initial 1.22, 0, 0; Change −2x, +x, +x; Equilibrium 0.71, 0.26, 0.26. Since 42% of BrCl decomposed, P(BrCl decomposed) = (0.42)(1.22 atm) = 0.51 atm = 2x, so x = 0.26 atm. 1 point for the correct stoichiometric (ICE) values at equilibrium. Keq = $(0.26)(0.26)/(0.71)^2 = 0.13$. 1 point for a Keq value consistent with the student's ICE table (a molar-concentration-based solution also earns full credit).

Solution 2

(g)

Mark scheme

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

Question 7

2015 ▪ Q7

Aluminum metal can be recycled from scrap metal by melting the metal to evaporate impurities.

(a) Calculate the amount of heat needed to purify 1.00 mole of Al originally at 298 K by melting it. The melting point of Al is 933 K. The molar heat capacity of Al is 24 J/(mol · K), and the heat of fusion of Al is 10.7 kJ/mol.

(b) The equation for the overall process of extracting Al from Al_2O_3 is shown below. Which requires less energy, recycling existing Al or extracting Al from Al_2O_3? Justify your answer with a calculation.

$$\mathrm{Al_2O_3}(s) \rightarrow 2\mathrm{Al}(s) + \frac{3}{2}\mathrm{O_2}(g) \qquad \Delta H^\circ = 1675\ \mathrm{kJ/mol}_{rxn}$$

Solution 7

(a)

Mark scheme

- To raise the temperature of 1.00 mol Al from 298 K to its melting point, 933 K: q = 24 J/(mol*K) x 1.00 mol x (933-298) K = 24 J/(mol*K) x 1.00 mol x 635 K = 15,000 J = 15 kJ (1 point for correctly calculating the heat needed to raise the temperature to 933 K). Then add the heat of fusion needed to melt the Al once at its melting point: 15 kJ + 10.7 kJ = 26 kJ total heat needed to purify (melt) the 1.00 mol Al (1 point for adding the heat of fusion to the previous result to reach the final answer, 26 kJ).

Solution 7

(b)

Mark scheme

- For extracting Al from Al2O3: the given reaction produces 2 mol Al per mol_rxn releasing/requiring 1675 kJ, so per mole of Al: 1675 kJ/mol_rxn x (1 mol rxn / 2 mol Al) = 837.5 kJ per mole of Al (1 point for a calculation that puts recycling and extraction on the same per-mole-Al basis for a fair comparison). Because 26 kJ (the recycling/melting energy from part (a)) is far less than 837.5 kJ (the energy to extract 1 mol Al from Al2O3), recycling existing Al requires less energy than extracting Al from its ore (1 point for the correct comparison and conclusion).

Question 6

2014 ▪ Q6

A student places a mixture of plastic beads consisting of polypropylene (PP) and polyvinyl chloride (PVC) in a 1.0 L beaker containing distilled water. After stirring the contents of the beaker vigorously, the student observes that the beads of one type of plastic sink to the bottom of the beaker and the beads of the other type of plastic float on the water. The chemical structures of PP and PVC are represented by the diagrams below, which show segments of each polymer.

[Structural diagram of PP: a repeating polymer backbone $-C(H)(CH_3) - C(H)(H)-$ shown as three repeat units, the middle one in brackets with subscript *n*, labeled "PP".]

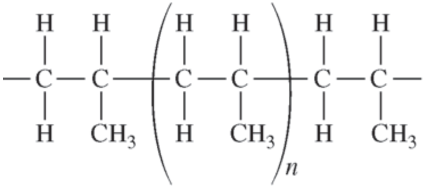
[Structural diagram of PVC: a repeating polymer backbone $-C(H)(Cl) - C(H)(H)-$ shown as three repeat units, the middle one in brackets with subscript *n*, labeled "PVC".]

Question 6

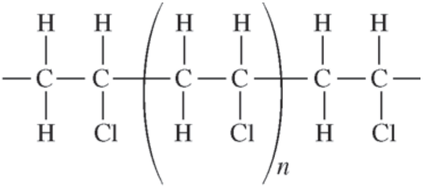
(a) Given that the spacing between polymer chains in PP and PVC is similar, the beads that sink are made of which polymer? Explain.

Question 6

float on the water. The chemical structures of PP and PVC are represented by the diagrams below, segments of each polymer.



PP

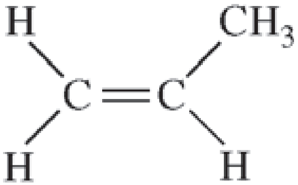


PVC

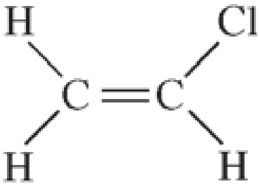
Question 6

Substance	$C_2H_3Cl(g)$	$C_3H_6(g)$	$CO_2(g)$	$H_2O(g)$	$HCl(g)$	$O_2(g)$
Standard Enthalpy of Formation (kJ/mol)	37	21	–394	–242	–92	0

Question 6



Propene



Vinyl Chloride (chloroethene)

Question 6

2014 ▪ Q6

A student places a mixture of plastic beads consisting of polypropylene (PP) and polyvinyl chloride (PVC) in a 1.0 L beaker containing distilled water. After stirring the contents of the beaker vigorously, the student observes that the beads of one type of plastic sink to the bottom of the beaker and the beads of the other type of plastic float on the water. The chemical structures of PP and PVC are represented by the diagrams below, which show segments of each polymer.

[Structural diagram of PP: a repeating polymer backbone $-C(H)(CH_3) - C(H)(H)-$ shown as three repeat units, the middle one in brackets with subscript *n*, labeled "PP".]

[Structural diagram of PVC: a repeating polymer backbone $-C(H)(Cl) - C(H)(H)-$ shown as three repeat units, the middle one in brackets with subscript *n*, labeled "PVC".]

(b) PP is synthesized from propene, C_3H_6, and PVC is synthesized from vinyl chloride, C_2H_3Cl. The structures of the molecules are shown below.

Question 6

[Structural diagram of Propene: $H_2C = CH(CH_3)$, drawn with H and CH_3 on one carbon and two H atoms on the other.]
[Structural diagram of Vinyl Chloride (chloroethene): $H_2C = CHCl$, drawn with H and Cl on one carbon and two H atoms on the other.]
The boiling point of liquid propene (226 K) is lower than the boiling point of liquid vinyl chloride (260 K). Account for this difference in terms of the types and strengths of intermolecular forces present in each liquid.

Question 6

2014 ▪ Q6

A student places a mixture of plastic beads consisting of polypropylene (PP) and polyvinyl chloride (PVC) in a 1.0 L beaker containing distilled water. After stirring the contents of the beaker vigorously, the student observes that the beads of one type of plastic sink to the bottom of the beaker and the beads of the other type of plastic float on the water. The chemical structures of PP and PVC are represented by the diagrams below, which show segments of each polymer.

[Structural diagram of PP: a repeating polymer backbone $-C(H)(CH_3)-C(H)(H)-$ shown as three repeat units, the middle one in brackets with subscript *n*, labeled "PP".]

[Structural diagram of PVC: a repeating polymer backbone $-C(H)(Cl)-C(H)(H)-$ shown as three repeat units, the middle one in brackets with subscript *n*, labeled "PVC".]

(c) In a separate experiment, the student measures the enthalpies of combustion of propene and vinyl chloride. The student determines that the combustion of 2.00 mol of vinyl chloride releases 2300 kJ of energy, according to the equation below.

Question 6

$$2\,C_2H_3Cl(g) + 5\,O_2(g) \rightarrow 4\,CO_2(g) + 2\,H_2O(g) + 2\,HCl(g) \qquad \Delta H^\circ = -2300\ \text{kJ/mol}_{rxn}$$

Using the table of standard enthalpies of formation below, determine whether the combustion of 2.00 mol of propene releases more, less, or the same amount of energy that 2.00 mol of vinyl chloride releases. Justify your answer with a calculation. The balanced equation for the combustion of 2.00 mol of propene is
$2\,C_3H_6(g) + 9\,O_2(g) \rightarrow 6\,CO_2(g) + 6\,H_2O(g)$.

Substance	$C_2H_3Cl(g)$	$C_3H_6(g)$	$CO_2(g)$	$H_2O(g)$	$HCl(g)$	$O_2(g)$
Standard Enthalpy of Formation (kJ/mol)	37	21	-394	-242	-92	0

Solution 6

(a)

Mark scheme

- The PVC beads sink. Since the spacing between polymer chains in PP and PVC is similar, density is set by mass: a Cl atom (in PVC's repeat unit) has a greater mass than the CH3 group (in PP's repeat unit), making PVC denser than water while PP is less dense, so PVC sinks and PP floats.

Solution 6

(b)

Mark scheme

- Both substances experience London dispersion forces, but vinyl chloride is polar (has a C–Cl bond) and so also has dipole-dipole interactions, whereas propene is essentially nonpolar with only LDFs. Vinyl chloride's Cl atom also gives it a larger, more polarizable electron cloud. As a result, intermolecular attractions are stronger overall in vinyl chloride, giving it the higher boiling point (260 K vs. 226 K for propene).

Solution 6

(c)

Mark scheme

- Balanced combustion of propene: $2\,C_3H_6(g) + 9\,O_2(g) \rightarrow 6\,CO_2(g) + 6\,H_2O(g)$. Using standard enthalpies of formation (kJ/mol: C3H6=21, CO2=−394, H2O=−242, O2=0): $\Delta H^\circ = [6(-394) + 6(-242)] - 2(21) = -3858$ kJ/mol$_{rxn}$ (1 point for this calculation). Since 2.00 mol vinyl chloride releases 2300 kJ but 2.00 mol propene releases 3858 kJ, the combustion of propene releases more energy (1 point for the correct comparison consistent with the calculated value).