2023

AP® Chemistry

Sample Student Responses and Scoring Commentary

Inside:

Free-Response Question 2

☑ Scoring Guidelines

☑ Student Samples

☑ Scoring Commentary

Question 2: Long Answer — 10 points

(a) For the correct calculated value reported with the correct number of significant figures: **1 point**

$$1.25 \text{ mol AlCl}_3 \times \frac{3 \text{ mol Cl}}{1 \text{ mol AlCl}_3} \times \frac{35.45 \text{ g Cl}}{1 \text{ mol Cl}} = 133 \text{ g Cl}$$

(b) For the correct algebraic manipulation of either ΔH_2° or ΔH_4° (may be implicit): **1 point**

Accept one of the following:

- *Reversing reaction 2:*

  $AlCl_3(g) \rightarrow Al(s) + \frac{3}{2}Cl_2(g) \quad \Delta H_{rxn}^\circ = -(-583) = +583 \text{ kJ/mol}_{rxn}$

- *Multiplying reaction 4 by $\frac{3}{2}$:*

  $\frac{3}{2}(Cl_2(g) \rightarrow 2\,Cl(g)) \quad \Delta H_{rxn}^\circ = \frac{3}{2}(+243) = +365 \text{ kJ/mol}_{rxn}$

For the correct calculated value: **1 point**

$$\Delta H_1^\circ = -\Delta H_2^\circ + \Delta H_3^\circ + 1.5(\Delta H_4^\circ) = -(-583) + 326 + 1.5(243) = 1274 \text{ kJ/mol}_{rxn}$$

Total for part (b) — 2 points

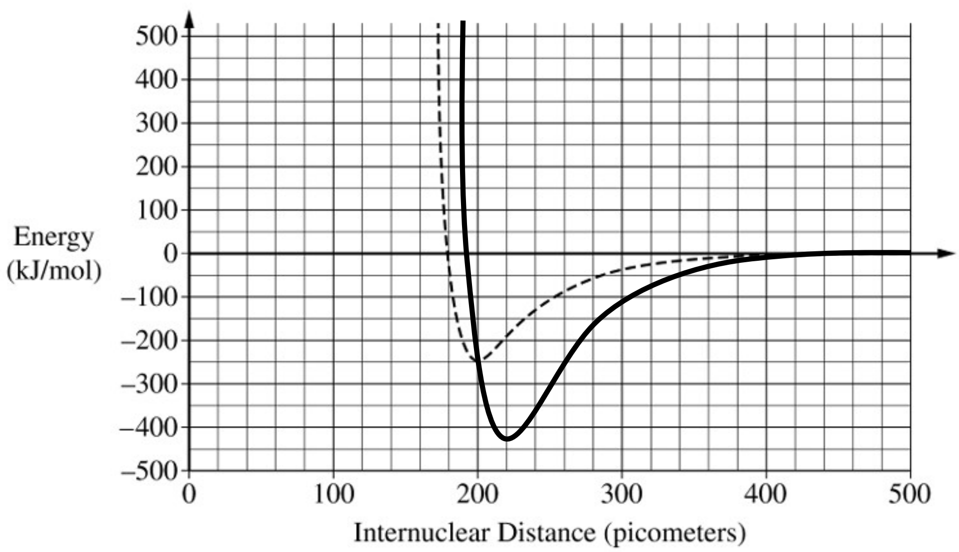
(c) (i) For the correct answer: **1 point**

200 picometers (±10 pm)

(ii) For a curve with a minimum at an internuclear distance of 220 ± 10 pm: **1 point**

See sample curve below

For a curve with a minimum energy value of -425 ± 20 kJ/mol that approaches zero as the internuclear distance approaches 500 pm: **1 point**



Total for part (c) — 3 points

(d) (i)	For the correct answer and a valid justification: *Diagram 2. Al has four electron domains in Diagram 2, which would be trigonal pyramidal, not trigonal planar.*	**1 point**
(ii)	For the correct answer and a valid justification: *Diagram 1. All atoms in diagram 1 have a formal charge of zero, whereas atoms in diagrams 2 and 3 have nonzero formal charges.*	**1 point**
	Total for part (d)	**2 points**
(e)	For the correct answer: $K_p = \frac{P_{Al_2Cl_6}}{(P_{AlCl_3})^2}$	**1 point**
(f)	For the correct calculated value, consistent with part (e): $K_p = \frac{\chi_{Al_2Cl_6}(P_{total})}{\left(\chi_{AlCl_3}(P_{total})\right)^2} = \frac{\frac{3}{10}(22.1)}{\left(\frac{7}{10}(22.1)\right)^2} = 0.0277$	**1 point**
	Total for question 2	**10 points**

Question 2

Begin your response to QUESTION 2 on this page.

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.

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

(a) How many grams of $Cl(g)$ can be formed from 1.25 mol of $AlCl_3(g)$?

$$\frac{1.25 \text{ mol } AlCl_3}{} \left| \frac{3 \text{ mol Cl}}{1 \text{ mol } AlCl_3} \right| \frac{35.45 g}{1 \text{ mol Cl}} = \boxed{133 g \text{ Cl}}$$

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

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

$AlCl_{3(g)} \longrightarrow \cancel{Al_{(s)}} + \cancel{\frac{3}{2} Cl_{2(g)}}$ +583

$\cancel{Al_{(s)}} \longrightarrow Al_{(g)}$ +326

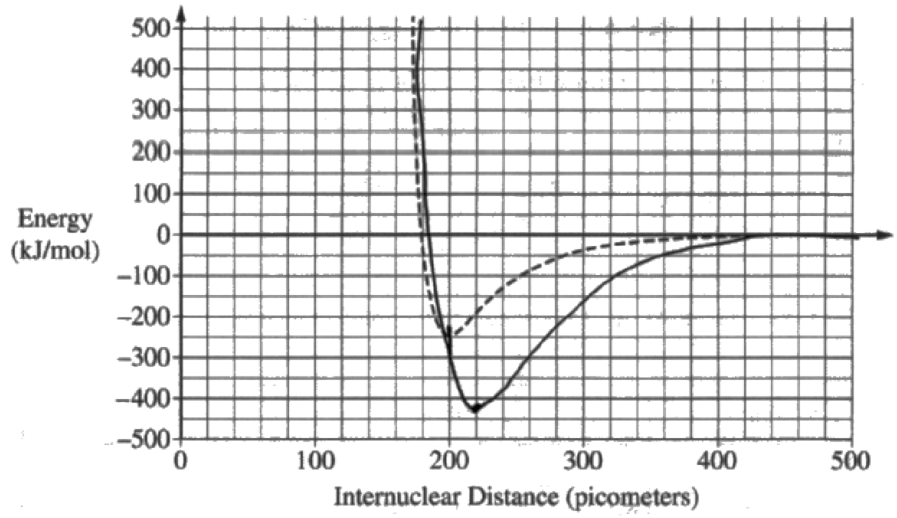
$\cancel{\frac{3}{2} Cl_{2(g)}} \longrightarrow 3Cl_{(g)}$ + 364.5

$AlCl_{3(g)} \longrightarrow Al_{(g)} + 3Cl_{(g)}$ $\boxed{1274 \text{ kJ}/mol_{rxn}}$

Question 2

Continue your response to QUESTION 2 on this page.

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



(i) Based on the graph, what is the bond length, in picometers, for Cl_2 ? 200 picometers

(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.

(d) Three proposed Lewis diagrams for the $AlCl_3(g)$ molecule are shown.

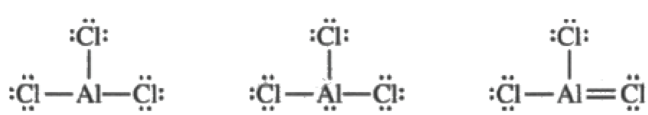


Diagram 1 Diagram 2 Diagram 3

(i) 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.

Diagram 2 can be eliminated because it has a molecular geometry of trigonal pyramidal. The central Al has three bonds and a lone pair, so it cannot be trigonal planar.

Question 2

Continue your response to **QUESTION 2** on this page.

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

Diagram 1 is best because all atoms have a formal charge of 0.

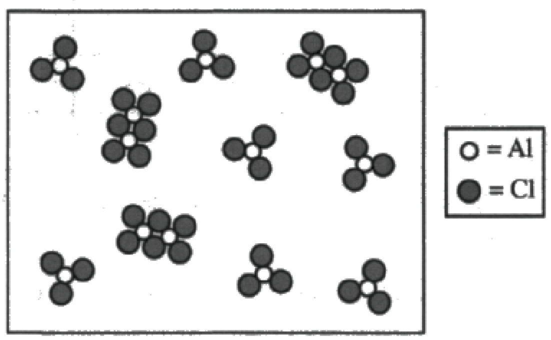
$AlCl_3$ is known to dimerize reversibly in the gas phase. The dimerization equilibrium is represented by the following equation.

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

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

$$K_p = \frac{P_{Al_2Cl_6}}{(P_{AlCl_3})^2}$$

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.



(f) 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.

$$P_{Al_2Cl_6} = \frac{3}{10} \cdot 22.1 = 6.63 \text{ atm}$$

$$P_{AlCl_3} = \frac{7}{10} \cdot 22.1 = 15.47 \text{ atm}$$

$$K_p = \frac{6.63}{(15.47)^2} = \boxed{0.0277}$$

Question 2

Begin your response to QUESTION 2 on this page.

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.

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

(a) How many grams of $Cl(g)$ can be formed from 1.25 mol of $AlCl_3(g)$?

$\frac{1.25 \text{ mol } AlCl_3}{} \cdot \frac{3 \text{ mol } Cl}{1 \text{ mol } AlCl_3} \cdot \frac{35.45 \text{ g}}{1 \text{ mol } Cl} = \boxed{133 \text{ g } Cl(g)}$

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

(b) Calculate the value of ΔH_1°, in kJ/mol$_{rxn}$, for reaction 1 above using reactions 2, 3, and 4.

$\boxed{AlCl_3(g)} \rightarrow \cancel{\frac{3}{2} Cl_2(g)} + \cancel{Al(s)}$ $\Delta H = +583$

$\cancel{Al(s)} \rightarrow \boxed{Al(g)}$ $\Delta H = +326$

$\cancel{\frac{3}{2} Cl_2(g)} \rightarrow \boxed{3Cl(g)}$ $\Delta H = +729$

$\boxed{\Delta H^\circ_1 = 1638 \text{ kJ/mol}_{rxn}}$

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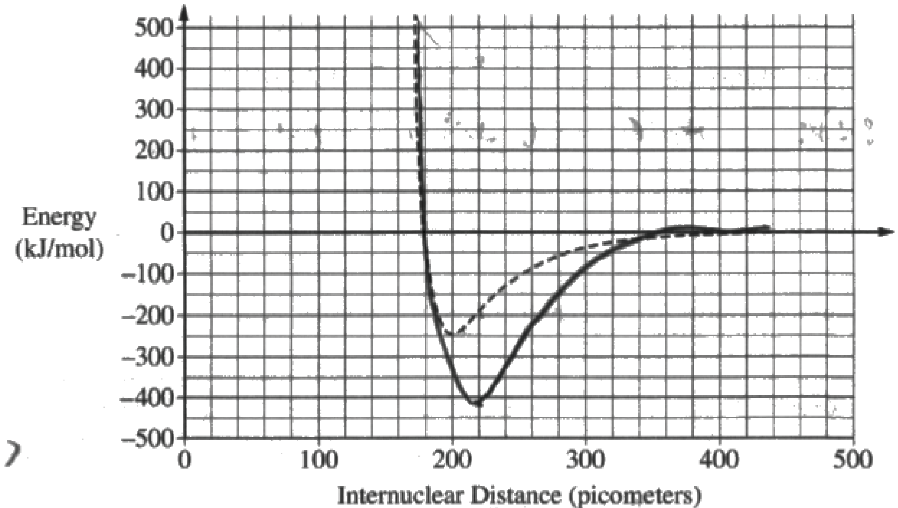
Question 2

Continue your response to QUESTION 2 on this page.

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



(i) Based on the graph, what is the bond length, in picometers, for Cl_2 ? 200 picometers

(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.

(d) Three proposed Lewis diagrams for the $AlCl_3(g)$ molecule are shown.

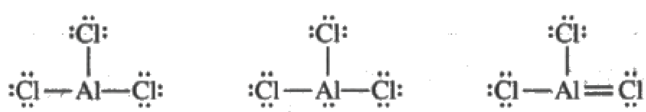


Diagram 1 Diagram 2 Diagram 3

(i) 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.

Diagram 2 can be eliminated. This is because of the lone pair of electrons. Trigonal planar geometries have only three electron domains, not four.

Question 2

Continue your response to **QUESTION 2** on this page.

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

Diagram 1. This is because in diagram one, the formal charge for each atom would be Ø.

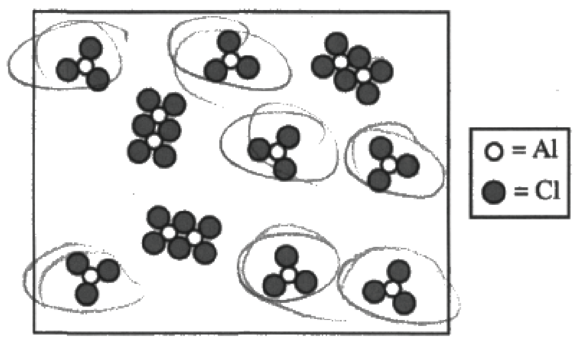
$AlCl_3$ is known to dimerize reversibly in the gas phase. The dimerization equilibrium is represented by the following equation.

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

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

$$K_p = \frac{(Al_2Cl_6)}{(AlCl_3)^2}$$

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.



(f) 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.

7mol $AlCl_3(g)$

Question 2

Begin your response to QUESTION 2 on this page.

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.

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

(a) How many grams of $Cl(g)$ can be formed from 1.25 mol of $AlCl_3(g)$?

$AlCl_3 = 27 + 35.5 \times 3$

$= 133.5\,g/mol$

$1.25\,mol = 166.88\,g$

~~Cl~~

$Cl = 166.88 \times 3$

$= 500.63\,g$

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

(b) Calculate the value of ΔH_1°, in kJ/mol$_{rxn}$, for reaction 1 above using reactions 2, 3, and 4.

$-563 + 326 + 243 = -14$

$\Delta H_1^\circ = -14$

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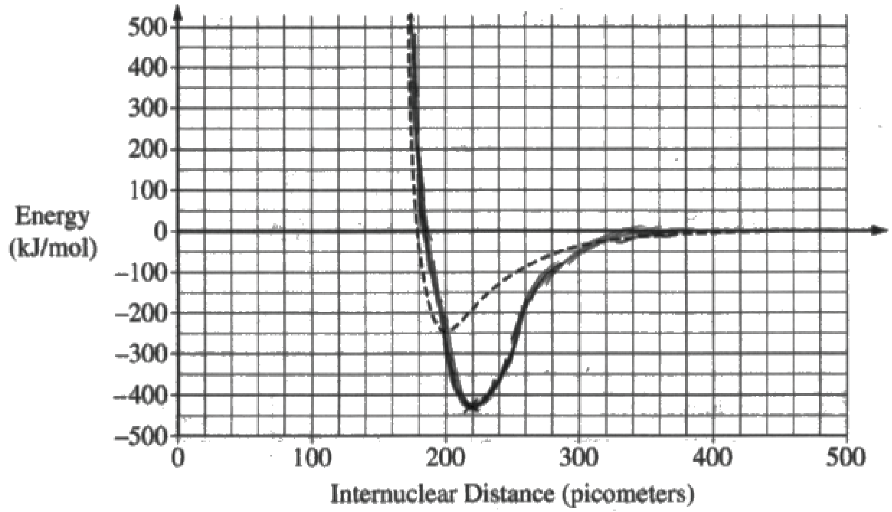
Question 2

Continue your response to QUESTION 2 on this page.

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



(i) Based on the graph, what is the bond length, in picometers, for Cl_2 ? 200

(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.

(d) Three proposed Lewis diagrams for the $AlCl_3(g)$ molecule are shown.

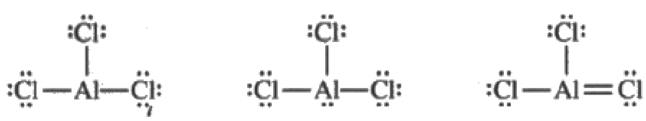


Diagram 1 Diagram 2 Diagram 3

(i) 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.

Diagram3, because it is a sp^3

Question 2

Continue your response to **QUESTION 2** on this page.

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

Diagram2, because it has a lone pair of electron on the Al

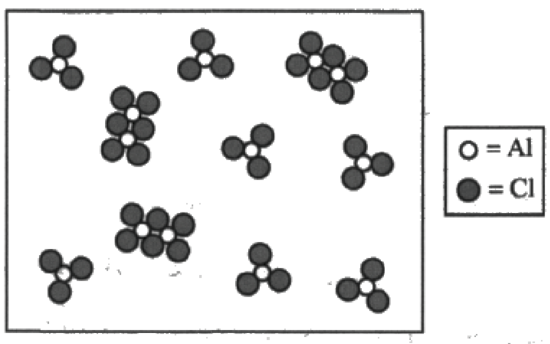
$AlCl_3$ is known to dimerize reversibly in the gas phase. The dimerization equilibrium is represented by the following equation.

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

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

$$K_p = \frac{[Al_2Cl_6]}{[AlCl_3]^2}$$

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.



(f) 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.

$AlCl_3 = 7$
$Al_2Cl_6 = 3$

$$K_p = \frac{7}{3^2}$$

$= 0.778$
$= 0.778$

Question 2

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

Question 2 presented students with a series of chemical reactions involving aluminum, chlorine, and the compound $AlCl_3$.

Part (a) of this question required students to apply the concepts of stoichiometry (Learning Objective SPQ-4.A, Skill 5.F from the *AP Chemistry Course and Exam Description*) to calculate the mass in grams of Cl(*g*) from a balanced equation that represents the decomposition of gaseous $AlCl_3$ into gaseous Al and gaseous Cl.

Part (b) asked students to apply the concepts of Hess's law (ENE-3.C, 5.F) to calculate the value of ΔH°_{rxn} for the decomposition reaction in part (a). Given a table of standard enthalpy values for three formation reactions, the first of two points was earned by either properly reversing the sign of ΔH_2 or multiplying the value of ΔH_4 by the factor of 3/2. The students earned the second point by correctly calculating the value of ΔH_1 for the overall reaction by manipulating both ΔH_2 and ΔH_4 correctly and adding them to ΔH_3.

Part (c)(i) required students to properly interpret a potential energy diagram to determine the bond length for molecular chlorine, Cl_2 (SAP-3.B, 5.D).

Part (c)(ii) provided the bond length and bond energy for the Al–Cl bond and asked the students to draw the potential energy diagram for the Al–Cl bond, indicating the correct bond length (1st point) and the correct bond energy (2nd point) (SAP-3.B, 3.A).

Part (d)(i) provided three Lewis diagrams of $AlCl_3$ and asked students to identify the one structure that is not representative of trigonal planar geometry using the principles of VSEPR theory (SAP-4.C, 6.E).

Part (d)(ii) asked students to identify which of the three provided Lewis diagrams was the best representation of $AlCl_3$ and justify that choice based on formal charges (SAP-4.B, 6.E).

Part (e) provided students with the dimerization reaction of $AlCl_3$ and required students to write the expression for the equilibrium constant, K_p, for the reaction (TRA-7.B, 5.B).

Part (f) prompted students to calculate the value of K_p using the equilibrium expression from part (e), the total pressure of the system, and a particle-level diagram that depicts the equilibrium mixture of $AlCl_3$ and Al_2Cl_6 (TRA-7.B, 5.F).

Sample: 2A
Score: 10

This response earned 10 points. In part (a) the point was earned for the correct calculated value reported with the correct number of significant figures. In part (b) the first point was earned for the correct manipulation of reaction 2 and/or reaction 4. The second point was earned for the correct

Question 2 (continued)

calculated value using Hess's Law. In part (c)(i) the point was earned for the correct bond length. In part (c)(ii) the first point was earned for drawing a curve with a minimum at an internuclear distance of 220 pm (±10 pm). The second point was earned for drawing the curve with a minimum energy value at –425 kJ/mol (±20 kJ/mol) that approaches zero as the internuclear distance approaches 500 pm. In part (d)(i) the point was earned for choosing diagram 2 and correctly explaining that diagram 2 has trigonal pyramidal geometry. In part (d)(ii) the point was earned for choosing diagram 1 and providing a valid justification that each atom in diagram 1 has a formal charge of zero. In part (e) the point was earned for the correct K_p expression. In part (f) the point was earned for using the correct partial pressure values for Al_2Cl_6 and $AlCl_3$ and reporting the correct calculated value for K_p.

Sample: 2B
Score: 7

This response earned 7 points. In part (a) the point was earned for the correct calculated value reported to the correct number of significant figures. In part (b) the first point was earned for the correct manipulation of reaction 2. The second point was not earned because the value of $\Delta H°$ for the manipulated version of reaction 4 is incorrect, giving an incorrect value for ΔH_1°. In part (c)(i) the point was earned for the correct bond length. In part (c)(ii) the first point was earned for drawing a curve with a minimum at an internuclear distance of 220 pm (±10 pm). The second point was earned for drawing the curve with a minimum energy value at –425 kJ/mol (±20 kJ/mol) that approaches zero as the internuclear distance approaches 500 pm. In part (d)(i) the point was earned for choosing diagram 2 and stating that diagram 2 cannot have trigonal planar geometry because it has four electron domains. In part (d)(ii) the point was earned for correctly choosing diagram 1 and providing a valid justification that all atoms in diagram 1 have a formal charge of zero. In part (e) no point was earned because "P" is not included in the equilibrium expression for the reaction. In part (f) no point was earned because no calculation of K_p is provided.

Sample: 2C
Score: 3

This response earned 3 points. In part (a) no point was earned because the calculation is done incorrectly. In part (b) the first point was not earned because $\Delta H°$ for neither reaction 2 nor reaction 4 is manipulated correctly. The second point was not earned because the value of ΔH_1° is incorrect. In part (c)(i) the point was earned for the correct bond length. In part (c)(ii) the first point was earned for drawing a curve with a minimum at an internuclear distance of 220 pm (±10 pm). The second point was earned for drawing the curve with a minimum energy value at –425 kJ/mol (± 20 kJ/mol) that approaches zero as the internuclear distance approaches 500 pm. In part (d)(i) no point was earned because diagram 3 is incorrectly selected. Additionally, the justification provided is based on hybridization instead of geometry. In part (d)(ii) no point was earned because diagram 2 is incorrectly selected. Additionally, the justification provided is not based on formal charges. In part (e) no point was earned because "P" is not included in the equilibrium expression for the reaction. Also, the brackets represent molarity, not partial pressure. In part (f) no point was earned because the calculated value for K_p is incorrect.