2022

AP® CollegeBoard

AP® Chemistry

Sample Student Responses and Scoring Commentary

Inside:

Free-Response Question 2

☑ Scoring Guidelines

☑ Student Samples

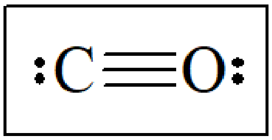
☑ Scoring Commentary

Question 2: Long Answer — 10 points

(a) For the correct answer and a valid justification: **1 point**

The H atoms are reduced because they change from an oxidation number of +1 to 0.

(b) For the correct answer: **1 point**



(c) (i) For the correct stoichiometry (may be implicit): **1 point**

$$\Delta S^\circ_{rxn} = \Sigma\Delta S^\circ_{products} - \Sigma\Delta S^\circ_{reactants}$$

$$\Delta S^\circ_{rxn} = \left(\Delta S^\circ_{CO(g)} + 2(\Delta S^\circ_{H_2(g)})\right) - \left(\Delta S^\circ_{CH_3OH(g)}\right)$$

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

$$\Delta S^\circ_{rxn} = 198 + 2(131) - 240. = 220.\ \frac{\text{J}}{\text{K}\cdot\text{mol}_{rxn}}$$

(ii) For the correct calculated value: **1 point**

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$

$$\Delta G^\circ = 90.0\ \frac{\text{kJ}}{\text{mol}_{rxn}} - (375\text{ K})(0.220\ \frac{\text{kJ}}{\text{K}\cdot\text{mol}_{rxn}}) = +7.5\text{ kJ/mol}_{rxn}$$

Total for part (c) — 3 points

(d) For the correct calculated value: **1 point**

$$P_{CO} = \frac{3}{10}(12.0\text{ atm}) = 3.6\text{ atm}$$

(e) For the correct expression: **1 point**

$$K_p = \frac{(P_{CO})(P_{H_2})^2}{(P_{CH_3OH})}$$

(f) For the correct calculated value: **1 point**

$$K_p = \frac{(P_{CO})(P_{H_2})^2}{(P_{CH_3OH})} = \frac{(4.2)(8.4)^2}{(2.7)} = 110$$

(g)	For a correct comparison of Q and K:	**1 point**

Accept one of the following:

- *The change in 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 decrease of the numerator in Q will be larger than that in the denominator, making* $Q_p < K_p$.
- $Q_p = \dfrac{\left(\dfrac{P_{CO}}{2}\right)\left(\dfrac{P_{H_2}}{2}\right)^2}{\left(\dfrac{P_{CH_3OH}}{2}\right)} = \dfrac{K_p}{4} \approx 27 < K_p$

For the correct answer and a valid justification: **1 point**

Decrease. Given that $Q_p < K_p$*, the partial pressures (moles) of the products will increase as equilibrium re-establishes, decreasing the number of moles of* CH_3OH.

Total for part (g) **2 points**

Total for question 2 **10 points**

Question 2

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

$$CH_3OH(g) \rightleftarrows CO(g) + 2\ H_2(g) \qquad \Delta H^\circ = \ 90.0\ \text{kJ} / \text{mol}_{rxn}$$

2. 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.

The hydrogen atoms are reduced. Since reduction is the gaining of electrons, the hydrogens oxidation number should decrease, which it does from +1 to 0.

(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.

:C≡O:

10
~~8~~
~~6~~
4

(c) 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))
$CH_3OH(g)$	240.
$CO(g)$	198
$H_2(g)$	131

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

$$(2(131) + 198) - 240 = 220\ \text{J}/\text{K}{\cdot}\text{mol}_{rxn}$$

Question 2

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

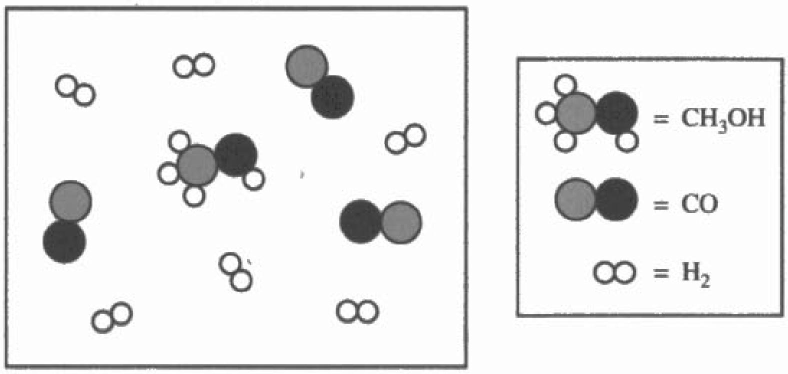
(ii) Calculate the value of $\Delta G°$, in kJ/mol$_{rxn}$, for the reaction at 375 K. Assume that $\Delta H°$ and $\Delta S°$ are independent of temperature.

$$\Delta G = \Delta H - T\Delta S$$

$$\Delta G = 90.0 - (375)(0.22)$$

$$\Delta G = +7.5 \text{ kJ/mol}_{rxn}$$

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



(d) 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.

$\frac{3}{10}$ = 30% of pressure is CO

$12 \cdot 0.3 = 3.6 \text{ atm} = P_{CO}$

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

$$K_p = \frac{(P_{H_2})^2 (P_{CO})}{(P_{CH_3OH})}$$

GO ON TO THE NEXT PAGE.

Question 2

Continue your response to QUESTION 2 on this page.

$$CH_3OH(g) \rightleftarrows CO(g) + 2\,H_2(g)$$

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.

Substance	Partial Pressure at Different Temperature
$CH_3OH(g)$	2.7 atm
$CO(g)$	4.2 atm
$H_2(g)$	8.4 atm

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

$$K_p = \frac{(P_{H_2})^2 (P_{CO})}{(P_{CH_3OH})} = \frac{(8.4)^2 (4.2)}{(2.7)} = 109.76$$

$110 = K_p$

(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 $CH_3OH(g)$ 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.

The amount of moles of CH_3OH will decrease.

Since $P_1V_1 = P_2V_2$, when V doubles, P will be halved

$P_{CH_3OH} = 1.35$ atm

$P_{H_2} = 4.2$ atm

$P_{CO} = 2.1$ atm

$Q = \frac{(2.1)(4.2)^2}{1.35} = 27.44 < 110 = K_p$

Since $Q < K_p$, the reaction will shift to produce more products and use up the reactants, thus lowering the amount of CH_3OH in the container

Question 2

Begin your response to QUESTION 2 on this page.

$CH_3OH(g) \rightleftarrows CO(g) + 2\, H_2(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$

2. 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.

The hydrogen atoms are being reduced since they are going from 1+ to 0, they are gaining electrons.

(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.

:C=Ö.

6
4
—
10

:C=Ö:

(c) 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))
$CH_3OH(g)$	240.
$CO(g)$	198
$H_2(g)$	131

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

P − R

198 2 × 131	240
460	− 240

$\Delta S = 220$

Question 2

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

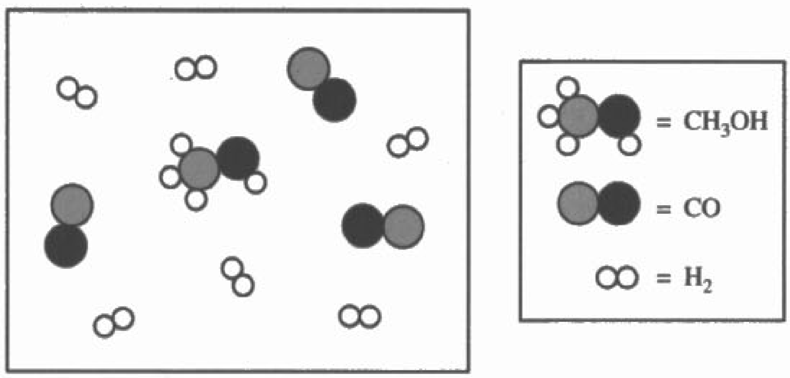
(ii) Calculate the value of $\Delta G°$, in kJ/mol$_{rxn}$, for the reaction at 375 K. Assume that $\Delta H°$ and $\Delta S°$ are independent of temperature.

$\Delta G = \Delta H - T\Delta S$

$\Delta G = 90 - (375 \cdot 220)$

$\Delta G = -82{,}410$

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



(d) 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.

$PV = nrt$

$12(1) = n\ .08\ 375$

$12 \times \frac{3}{10}$

3.6atm

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

$K_p = \frac{(3.6)(7.2)^2}{(1.2)}$

Question 2

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

$$CH_3OH(g) \rightleftarrows CO(g) + 2\ H_2(g)$$

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.

Substance	Partial Pressure at Different Temperature
$CH_3OH(g)$	2.7 atm
$CO(g)$	4.2 atm
$H_2(g)$	8.4 atm

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

$$K_p = \frac{(4.2)(8.4)^2}{(2.7)}$$

$$K_p = 109.76 \text{ atm}$$

(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 $CH_3OH(g)$ 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.

Since $Q > K$ the reaction will shift to make more Products. CH_3OH moles will decrease according to Lachatlier's Principle.

Question 2

Begin your response to QUESTION 2 on this page.

$CH_3OH(g) \rightleftarrows CO(g) + 2\ H_2(g) \qquad \Delta H° = 90.0\ kJ/mol_{rxn}$

2. 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.

reduced

(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.

(c) 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))
$CH_3OH(g)$	240.
$CO(g)$	198
$H_2(g)$	131

(i) Use the data in the table to calculate the value of the standard entropy change, $\Delta S°$, in $J/(K{\cdot}mol_{rxn})$, for the reaction.

$\Delta S = \sum S°_{products} - \sum S°_{reactants}$

$= (198) + 2(131) - (240)$

$= 220\ J/K{\cdot}mol_{rxn}$

GO ON TO THE NEXT PAGE.

Question 2

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

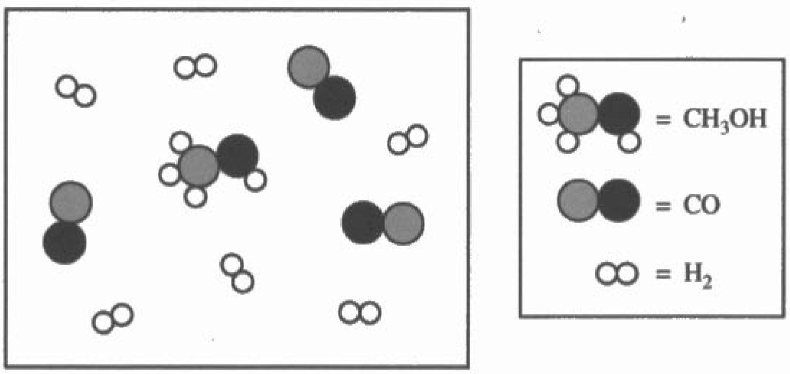
(ii) Calculate the value of $\Delta G°$, in kJ/mol$_{rxn}$, for the reaction at 375 K. Assume that $\Delta H°$ and $\Delta S°$ are independent of temperature.

$\Delta G = \Delta H - \Delta S$

$= 90 - 220$

$= -130$ kJ/mol$_{rxn}$

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



(d) 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.

$\frac{3}{12} = 3$ atm

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

$K_p = \frac{(CO)(H_2)^2}{(CH_3OH)}$

GO ON TO THE NEXT PAGE.

Question 2

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

$$CH_3OH(g) \rightleftarrows CO(g) + 2\ H_2(g)$$

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.

Substance	Partial Pressure at Different Temperature
$CH_3OH(g)$	2.7 atm
$CO(g)$	4.2 atm
$H_2(g)$	8.4 atm

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

$$K_p = \frac{(8.4)^2(4.2)}{2.7}$$

$$= 109.76$$

(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 $CH_3OH(g)$ 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.

It decreases

GO ON TO THE NEXT PAGE.

Question 2

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

Overview

Question 2 exposed students to a variety of prompts concerning the decomposition of methanol.

Part (a) of this question required the students to identify if an atom has been oxidized or reduced and to justify in terms of oxidation numbers (Learning Objective TRA-2.A, Science Practice 4.A from the *AP Chemistry Course and Exam Description*).

Part (b) asked students to complete the Lewis structure for a diatomic molecule (SAP-4.A, 3.B).

Part (c) consisted of two parts. Given a table of standard entropies of formation, students were asked to determine the standard entropy of reaction, $\Delta S°$, in part (c)(i). Using this calculated value, students were asked in part (c)(ii) to determine the standard Gibbs free energy of reaction, $\Delta G°$, using the provided value for the standard enthalpy of reaction, $\Delta H°$. Part (c)(i) was worth 2 points, and (c)(ii) was worth 1 point. In part (c)(i) the first point hinged on students using the given standard molar entropies and setting up the calculation of $\Delta S°$ using the correct reaction stoichiometry (ENE-4.B, 5.B). The second point was earned for the correct calculated value of $\Delta S°$ (ENE-4.B, 5.F). Part (c)(ii) asked students to use the value of $\Delta S°_{rxn}$ determined in part (c)(i), along with the provided value of $\Delta H°$ to calculate the $\Delta G°$ (ENE-4.C, 5.F).

In part (d) students were asked to interpret a particle drawing and calculate the partial pressure of CO at equilibrium based on the mole fraction of each component of the gas mixture and the total pressure of the mixture at equilibrium. (SAP-7.A, 5.D).

Part (e) asked students to write a K_p expression (TRA-7.B, 5.F) given a balanced gas-phase reaction.

Utilizing the K_p expression determined in part (e), students were provided the equilibrium partial pressure for all gas species and asked to calculate the value of K_p in part (f) (TRA-8.B, 5.C).

Part (g) was worth 2 points. Students were asked to make a claim about how the moles of the reactant gas will change when the volume of the system is doubled (TRA-8.B, 5.C) for the first point. The second point was then associated with the subsequent justification of their claim (TRA-8.B, 6.D).

Sample: 2A
Score: 10

This response earned 10 points. For part (a) the point was earned because the response correctly states that hydrogen atoms are reduced and gives the correct oxidation numbers. For part (b) the point was earned for the correct Lewis electron-dot diagram. For part (c)(i) the points were earned for the correct value of $\Delta S°$. For part (c)(ii) the point was earned for the correct value of $\Delta G°$. In part (d) the point was earned for the correct partial pressure of CO. In part (e) the point was earned for the correct K_p expression. In part (f) the point was earned for the correct value of K_p. In part (g) the points were earned because the response correctly states that the number of moles of CH_3OH decreases, provides a correct calculation of Q, and has a correct comparison of Q and K_p.

Question 2 (continued)

Sample: 2B
Score: 5

This response earned 5 points. In part (a) the point was earned because the response states that the hydrogen atoms are being reduced and gives the correct oxidation numbers. In part (b) no point was earned because the C atom does not follow the octet rule. In part (c)(i) the points were earned for the correct answer with the correct stoichiometry and setup (products – reactants). In part (c)(ii) no point was earned because the response fails to convert the J in $\Delta S°$ to kJ. In part (d) the point was earned for the correct calculated value. In part (e) no point was earned because the response does not include a K_p expression. In part (f) the point was earned for the correct calculated value of K_p. The significant figure error was ignored. The points were not earned in part (g) because the response incorrectly states that $Q > K$ and that the number of moles of CH_3OH would decrease (which is inconsistent with Q being greater than K).

Sample: 2C
Score: 3

This response earned 3 points. In part (a) no point was earned because the response does not include the oxidation numbers for hydrogen. In part (b) no point was earned because the Lewis electron-dot diagram has too many electrons. In part (c)(i) the points were earned for the correct calculation of $\Delta S°$. In part (c)(ii) no point was earned because the calculation is missing the temperature, and the units for $\Delta H°$ and $\Delta S°$ are inconsistent. In part (d) no point was earned because the partial pressure given for CO is incorrect; the response incorrectly divides the number of particles of CO by the total pressure. In part (e) no point was earned because the K_p expression does not include the P for the partial pressure. In part (f) the point was earned for the correct calculation of K_p. The significant figure error was ignored. In part (g) neither point was earned because the response does not compare Q and K_p, nor does it include a justification as to why the number of moles of CH_3OH decreases.