2023

AP® Chemistry

Sample Student Responses and Scoring Commentary

Inside:

Free-Response Question 1

☑ Scoring Guidelines

☑ Student Samples

☑ Scoring Commentary

Question 1: Long Answer — 10 points

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

Accept one of the following:

- $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^5$
- $[\mathrm{Ar}]\, 4s^2 3d^5$

(ii) For the correct answer, consistent with part (a)(i): **1 point**

$4s$

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

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

$62.673\text{ g} - 61.262\text{ g} = 1.411\text{ g Cl}$

(c) For the correct calculated value, consistent with part (b): **1 point**

$$1.411\text{ g Cl} \times \frac{1\text{ mol Cl}}{35.45\text{ g Cl}} = 0.03980\text{ mol Cl}$$

(d) For the correct answer, consistent with part (c): **1 point**

$$\frac{0.03980\text{ mol Cl}}{0.0199\text{ mol Mn}} = \frac{2\text{ mol Cl}}{1\text{ mol Mn}} \Rightarrow \mathrm{MnCl_2}$$

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

Less than. If some of the mass of aqueous Mn_xCl_y *is lost due to splattering, the final mass of the dry beaker and* Mn_xCl_y *will be decreased, which will decrease the calculated mass and number of moles of chlorine in the dry solid.*

(f) (i)	For the correct balanced equation: $2\ \mathrm{MnO_2}(s) + \mathrm{H_2O}(l) + 2\ e^- \rightarrow \mathrm{Mn_2O_3}(s) + 2\ \mathrm{OH^-}(aq)$ $\mathrm{Zn}(s) + 2\ \mathrm{OH^-}(aq) \rightarrow \mathrm{ZnO}(s) + \mathrm{H_2O}(l) + 2\ e^-$ $2\ \mathrm{MnO_2}(s) + \mathrm{Zn}(s) \rightarrow \mathrm{Mn_2O_3}(s) + \mathrm{ZnO}(s)$	**1 point**
(ii)	For the correct calculated value, consistent with part (f)(i): $E^\circ_{cell} = 0.15\text{ V} - (-1.28\text{ V}) = 1.43\text{ V}$	**1 point**
(iii)	For the correct calculated value, consistent with part (f)(ii): $\Delta G^\circ = -nFE^\circ = -\frac{2\text{ mol } e^-}{1\text{ mol}_{rxn}} \times \frac{96{,}485\text{ C}}{1\text{ mol } e^-} \times \frac{1.43\text{ J}}{1\text{ C}} \times \frac{1\text{ kJ}}{1000\text{ J}} = -276\text{ kJ/mol}_{rxn}$	**1 point**
(iv)	For the correct answer and a valid justification: Accept one of the following: • *Disagree. The battery is enclosed, so no change in the total mass will occur.* • *Disagree. All reactants and products are in the solid phase, so the mass of the sealed battery will remain the same (no gases enter or exit the battery).*	**1 point**
	Total for part (f)	**4 points**
	Total for question 1	**10 points**

Question 1

Begin your response to **QUESTION 1** on this page.

CHEMISTRY
SECTION II
Time—1 hour and 45 minutes
7 Questions

Directions: Questions 1–3 are long free-response questions that require about 23 minutes each to answer and are worth 10 points each. Questions 4–7 are short free-response questions that require about 9 minutes each to answer and are worth 4 points each.

For each question, show your work for each part in the space provided after that part. Examples and equations may be included in your responses where appropriate. For calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer. Pay attention to significant figures.

1. Answer the following questions related to manganese compounds.

(a) Manganese has several common oxidation states.

(i) Write the complete electron configuration for an Mn atom in the ground state.

$[Ar]4s^2 3d^5$ or $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^5$

(ii) When manganese forms cations, electrons are lost from which subshell first? Identify both the number and letter associated with the subshell.

4s

A student performs an experiment to produce a manganese salt of unknown composition, $Mn_xCl_y(aq)$, and determine its empirical formula. The student places a sample of $Mn(s)$ in a beaker containing excess $HCl(aq)$, as represented by the following equation.

$$x\,Mn(s) + y\,HCl(aq) \rightarrow Mn_xCl_y(aq) + \frac{y}{2}H_2(g)$$

Question 1

Continue your response to **QUESTION 1** on this page.

The student heats the resulting mixture until only $Mn_xCl_y(s)$ remains in the beaker. The data are given in the following table.

Mass of empty beaker	60.169 g
Mass of beaker and Mn(*s*)	61.262 g
Mass of beaker and Mn_xCl_y after heating to constant mass	62.673 g

(b) Calculate the mass of Cl in the sample of $Mn_xCl_y(s)$ remaining in the beaker.

62.673g − 61.262g = 1.411g

(c) Calculate the number of moles of Cl in the sample of $Mn_xCl_y(s)$ remaining in the beaker.

$$1.411 g Cl \times \frac{1 mole Cl}{35.45 g Cl} = 0.0398 moles Cl$$

$$= 4.0 \times 10^{-2} molesCl$$

(d) The student determines that 0.0199 mol of Mn was used in the experiment. Use the data to determine the empirical formula of the $Mn_xCl_y(s)$.

$$y = \frac{0.0898}{0.0199} = 2.0$$

$$x = \frac{0.0199}{0.0199} = 1$$

$MnCl_2$

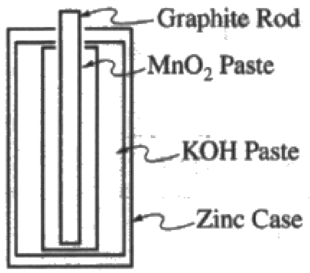
(e) The student repeats the experiment using the same amounts of Mn and HCl and notices that some of the Mn_xCl_y splatters out of the beaker as it is heated to dryness. Will the number of moles of Cl calculated for this trial be greater than, less than, or equal to the number calculated in part (c) ? Justify your answer.

The number of moles of Cl would be less than tu number of moles calculated in part (c) because the final mass of the beaker and Mn_xCl_y would be lower.

Question 1

Continue your response to QUESTION 1 on this page.

(f) Another compound of manganese, MnO_2, is used in alkaline batteries, represented by the following diagram. Some half-reactions are given in the table.



Reduction Half-Reaction	$E°$ (V)
$Zn^{2+}(aq) + 2\,e^- \rightarrow Zn(s)$	−0.76
$ZnO(s) + H_2O(l) + 2\,e^- \rightarrow Zn(s) + 2\,OH^-(aq)$	−1.28
$2\,MnO_2(s) + H_2O(l) + 2\,e^- \rightarrow Mn_2O_3(s) + 2\,OH^-(aq)$	0.15

(i) Based on the half-reactions given in the table, write the balanced net ionic equation for the reaction that has the greatest thermodynamic favorability.

$$2MnO_2(s) + \cancel{H_2O(l)} + \cancel{2e^-} \rightarrow Mn_2O_3(s) + \cancel{2OH^-(aq)} \quad \mathcal{E}° = 0.15V$$

$$+ \quad Zn(s) + \cancel{2OH^-(aq)} \longrightarrow ZnO(s) + \cancel{H_2O(l)} + \cancel{2e^-} \quad \mathcal{E}° = 1.28V$$

$$2MnO_2(s) + Zn(s) \longrightarrow Mn_2O_3(s) + ZnO(s) \quad \mathcal{E}° = 1.43V$$

(ii) Calculate the value of $E°_{cell}$ for the overall reaction.

$$\mathcal{E}° = 0.15V + 1.28V = 1.43V$$

(iii) Calculate the value of $\Delta G°$ in kJ/mol_{rxn}.

$$\Delta G° = -nF\mathcal{E}°$$

$$\Delta G° = -(2\text{ mol }e^-)(96485\ C/mol\ e^-)(1.43V)$$

$$= -275947\ J$$

$$\Delta G = -276\ kJ/mol$$

(iv) A student claims that the total mass of an alkaline battery decreases as the battery operates because the anode loses mass. Do you agree with the student's claim? Justify your answer.

I disagree with this claim because the cathode gains mass while the anode loses mass, so the total mass stays the same. The mass lost by the anode cannot disapear by the Law of conservation of mass, it becomes ions in the paste.

Begin your response to **QUESTION 1** on this page.

CHEMISTRY

SECTION II

Time—1 hour and 45 minutes

7 Questions

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1. Answer the following questions related to manganese compounds.

(a) Manganese has several common oxidation states.

(i) Write the complete electron configuration for an Mn atom in the ground state.

$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^5$

(ii) When manganese forms cations, electrons are lost from which subshell first? Identify both the number and letter associated with the subshell. They are lost from the 4s subshell because it is the outermost shell.

A student performs an experiment to produce a manganese salt of unknown composition, $Mn_xCl_y(aq)$, and determine its empirical formula. The student places a sample of Mn(*s*) in a beaker containing excess HCl(*aq*), as represented by the following equation.

$$x\ Mn(s) + y\ HCl(aq) \rightarrow Mn_xCl_y(aq) + \frac{y}{2} H_2(g)$$

Question 1

Continue your response to **QUESTION 1** on this page.

The student heats the resulting mixture until only $Mn_xCl_y(s)$ remains in the beaker. The data are given in the following table.

Mass of empty beaker	60.169 g
Mass of beaker and $Mn(s)$	61.262 g
Mass of beaker and Mn_xCl_y after heating to constant mass	62.673 g

(b) Calculate the mass of Cl in the sample of $Mn_xCl_y(s)$ remaining in the beaker.

$$61.262g - 60.169g = 1.093g\ Mn$$

$$62.673g - 60.196g = 2.504g\ Mn_xCl_y$$

$$2.504g\ Mn_xCl_y - 1.093g\ Mn = \boxed{1.411g\ Cl}$$

(c) Calculate the number of moles of Cl in the sample of $Mn_xCl_y(s)$ remaining in the beaker.

$$1.411g\left(\frac{1mol}{35.45g}\right) = \boxed{0.0398\ moles}$$

(d) The student determines that 0.0199 mol of Mn was used in the experiment. Use the data to determine the empirical formula of the $Mn_xCl_y(s)$.

$$0.0199 \approx 0.0200$$

$$0.0398 \approx 0.0400$$

$$Mn_2Cl_4 \longrightarrow \boxed{MnCl_2}$$

(e) The student repeats the experiment using the same amounts of Mn and HCl and notices that some of the Mn_xCl_y splatters out of the beaker as it is heated to dryness. Will the number of moles of Cl calculated for this trial be greater than, less than, or equal to the number calculated in part (c) ? Justify your answer.

The number of moles of Cl will remain the same because the concentration of [Mn] and [Cl] are the same and nothing is being done to change the reaction

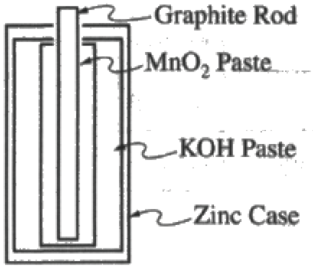
GO ON TO THE NEXT PAGE.

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Question 1

Continue your response to **QUESTION 1** on this page.

(f) Another compound of manganese, MnO_2, is used in alkaline batteries, represented by the following diagram. Some half-reactions are given in the table.



Reduction Half-Reaction	$E°$ (V)
$Zn^{2+}(aq) + 2e^- \rightarrow Zn(s)$	–0.76
$ZnO(s) + H_2O(l) + 2e^- \rightarrow Zn(s) + 2OH^-(aq)$	–1.28
$2MnO_2(s) + H_2O(l) + 2e^- \rightarrow Mn_2O_3(s) + 2OH^-(aq)$	0.15

(i) Based on the half-reactions given in the table, write the balanced net ionic equation for the reaction that has the greatest thermodynamic favorability.

$Zn(s) + 2OH^-(aq) \rightarrow ZnO(s) + H_2O(l) + 2e^-$

(ii) Calculate the value of $E°_{cell}$ for the overall reaction.

$$\begin{array}{r} -0.76 \\ 1.28 \\ + \underline{0.15} \end{array} \quad E° = 0.67$$

(iii) Calculate the value of $\Delta G°$ in kJ/mol_{rxn}.

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

(iv) A student claims that the total mass of an alkaline battery decreases as the battery operates because the anode loses mass. Do you agree with the student's claim? Justify your answer.

No. The battery decreases because the reaction reaches equillibrum and is thermodyramically favorable

Question 1

Begin your response to **QUESTION 1** on this page.

CHEMISTRY

SECTION II

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1. Answer the following questions related to manganese compounds.

(a) Manganese has several common oxidation states.

(i) Write the complete electron configuration for an Mn atom in the ground state.

$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^5$

(ii) When manganese forms cations, electrons are lost from which subshell first? Identify both the number and letter associated with the subshell.

$\boxed{4s^2}$ 4s

A student performs an experiment to produce a manganese salt of unknown composition, $Mn_xCl_y(aq)$, and determine its empirical formula. The student places a sample of $Mn(s)$ in a beaker containing excess $HCl(aq)$, as represented by the following equation.

$$x\,Mn(s) + y\,HCl(aq) \rightarrow Mn_xCl_y(aq) + \frac{y}{2}H_2(g)$$

GO ON TO THE NEXT PAGE.

Question 1

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Mass of empty beaker	**60.169 g**	
Mass of beaker and Mn(*s*)	**61.262 g**	1.093
Mass of beaker and Mn_xCl_y after heating to constant mass	**62.673 g**	2.504

(b) Calculate the mass of Cl in the sample of $Mn_xCl_y(s)$ remaining in the beaker.

$\frac{2.504}{6} = 0.41733$ 1210 2g

(c) Calculate the number of moles of Cl in the sample of $Mn_xCl_y(s)$ remaining in the beaker.

0.06 mol

(d) The student determines that 0.0199 mol of Mn was used in the experiment. Use the data to determine the empirical formula of the $Mn_xCl_y(s)$.

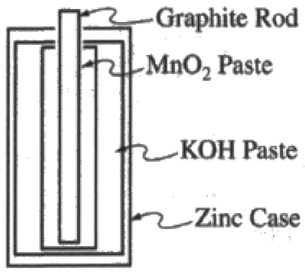
$MnCl_3$

(e) The student repeats the experiment using the same amounts of Mn and HCl and notices that some of the Mn_xCl_y splatters out of the beaker as it is heated to dryness. Will the number of moles of Cl calculated for this trial be greater than, less than, or equal to the number calculated in part (c) ? Justify your answer.

Equal to, because volume does not affect molarity. Losing some volume of Mn_xCl_y does not dillute or increase concentration.

Continue your response to QUESTION 1 on this page.

(f) Another compound of manganese, MnO_2, is used in alkaline batteries, represented by the following diagram. Some half-reactions are given in the table.



Reduction Half-Reaction	$E°$ (V)
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$2MnO_2(s) + H_2O(l) + 2e^- \rightarrow Mn_2O_3(s) + 2OH^-(aq)$	0.15

(i) Based on the half-reactions given in the table, write the balanced net ionic equation for the reaction that has the greatest thermodynamic favorability.

$2MnO_2 + H_2O + 2e^- \rightarrow Mn_2O_3 + 2OH^-$

(ii) Calculate the value of $E°_{cell}$ for the overall reaction.

$\boxed{-0.61}$

0.61

(iii) Calculate the value of $\Delta G°$ in kJ/mol$_{rxn}$.

$\Delta G° = -n \frac{96,485}{mol} \cdot -0.61$

$\Delta G° = -(0.0179)\frac{96,485}{mol} \cdot -0.61$

$\boxed{\Delta G° = 1200}$

(iv) A student claims that the total mass of an alkaline battery decreases as the battery operates because the anode loses mass. Do you agree with the student's claim? Justify your answer.

I do agree, as very slowly when charge goes through the anode metal, some mass e^- is taken with and slowly it will run out without replacement.

Question 1

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

Overview

Question 1 presented students with a variety of chemical situations involving manganese and its compounds.

Part (a)(i) required students to provide an electron configuration for the transition element manganese. The intent was for students to demonstrate understanding of the Aufbau principle using an appropriate representation for electron configuration (Learning Objective SAP-1.A, Skill 3.B from the *AP Chemistry Course and Exam Description*).

Part (a)(ii) required students to use the electron configuration determined in (a)(i) to identify which subshell loses electrons first when manganese atoms form cations. The intent was for students to demonstrate understanding of ion formation from the electronic structure of an atom (SAP-2.A, 4.A).

Parts (b), (c), (d), and (e) involved a chemical equation with unknown subscripts “x” and “y” for the formation of a Mn_xCl_y compound from the reaction between Mn(*s*) and HCl(*aq*). Students were given a set of experimental data to analyze, which contains the mass of an empty beaker, the mass of the empty beaker and Mn(*s*), and the mass of beaker and Mn_xCl_y(*s*) heated to constant mass.

Part (b) required students to calculate the mass of Cl in the dry Mn_xCl_y sample that remains in the beaker. The intent of the question was for students to use the experimental data provided to find the mass of Cl (SPQ-1.A, 5.F).

Part (c) required students to calculate the moles of Cl based on the mass of Cl determined in part (b) (SPQ-1.A, 5.F).

Part (d) required students to determine the empirical formula of the Mn_xCl_y sample using the moles of Cl determined in part (c) and a given quantity of moles of Mn (SPQ-2.A, 3.B).

Part (e) required students to explain how the moles of Cl calculated in part (c) would be affected in the event of an experimental error where a portion of the Mn_xCl_y splattered out of the beaker during the process of heating the product to dryness (SPQ-2.A, 6.G).

Part (f) of this question consisted of four parts that revolve around an alkaline battery containing MnO_2. Students were provided with a table containing three reduction half-reactions and the accompanying standard reduction potentials. One half-reaction contains MnO_2, and the other two half-reactions contain Zn.

Part (f)(i) required students to use the half-reactions given in the table to write the balanced net ionic equation representing the most thermodynamically favorable reaction (ENE-6.A, 5.E).

Part (f)(ii) required students to calculate the standard cell potential ($E°_{cell}$) for the overall reaction occurring in the battery (ENE-6.A, 5.F).

Question 1 (continued)

Part (f)(iii) required students to calculate the change in Gibbs free energy (ΔG°_{rxn}) for the reaction in part (f)(i), in units of kJ/mol$_{rxn}$, utilizing the mathematical relationship between ΔG°_{rxn} and E°_{cell} (ENE-6.B, 5.F).

Part (f)(iv) required students to evaluate a claim (agree or disagree and then provide a justification) that the total mass of the battery, a closed system, decreases during operation (ENE-6.A, 6.D).

Sample: 1A
Score: 10

This response earned 10 points. In part (a)(i) the point was earned for the correct electron configuration. In part (a)(ii) the point was earned for correctly identifying the subshell from which the electrons are lost first; the response is also consistent with the response to part (a)(i). In part (b) the point was earned for correctly calculating the mass of Cl remaining in the dry product using the experimental data provided; the answer is supported with work. In part (c) the point was earned for correctly converting the mass of Cl from part (b) into moles using the molar mass; supporting work is provided. In part (d) the point was earned for a correct empirical formula with supporting work showing a mole ratio calculation. In part (e) the point was earned for correctly indicating that the lower mass of the dry product results in fewer moles of Cl calculated. In part (f)(i) the point was earned for correctly writing the net ionic equation for the reaction with the greatest thermodynamic favorability; supporting work is provided. In part (f)(ii) the point was earned for correctly calculating E°_{cell} for the overall reaction consistent with part (f)(i). In part (f)(iii) the point was earned for correctly calculating ΔG° consistent with part (f)(ii). In part (f)(iv) the point was earned for disagreeing and providing a correct justification.

Sample: 1B
Score: 5

This response earned 5 points. In part (a)(i) the point was earned for the correct electron configuration. In part (a)(ii) the point was earned for correctly identifying the subshell from which the electrons are lost first; the response is also consistent with the response to part (a)(i). In part (b) the point was earned for correctly calculating the mass of Cl remaining in the dry product using the experimental data provided; the answer is supported with work. In part (c) the point was earned for correctly converting the mass of Cl from part (b) into moles using the molar mass; supporting work is provided. In part (d) the point was earned for a correct empirical formula with supporting work. In part (e) the point was not earned because the response incorrectly indicates that the number of moles of Cl remains the same because the concentrations of Mn and Cl are the same. In part (f)(i) the point was not earned because the net ionic equation provided is only the reverse of one half-reaction; it is not the net ionic equation for the reaction with the greatest thermodynamic favorability. In part (f)(ii) the point was not earned because the E°_{cell} calculated does not represent the reaction with the greatest thermodynamic favorability and is inconsistent with part (f)(i). In part (f)(iii) the point was not earned because the incorrect equation is given, and no answer or work is provided for ΔG°. In part (f)(iv) the point was not earned because the justification is not correct.

Question 1 (continued)

Sample: 1C
Score: 2

This response earned 2 points. In part (a)(i) the point was earned for the correct electron configuration. In part (a)(ii) the point was earned for correctly identifying the subshell from which the electrons are lost first. In part (b) the point was not earned because the calculation is incorrect. In part (c) the point was not earned because there is no work to support the calculation of number of moles of Cl, even though the answer given is consistent with part (b). The directions on the exam say, "For calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer." In part (d) the point was not earned because there is no work to support the empirical formula. In part (e) the point was not earned because the response incorrectly indicates that the number of moles of Cl will be equal to the number calculated in part (c) because volume does not affect molarity. In part (f)(i) the point was not earned because the net ionic equation provided is only a restatement of one half-reaction; it is not the net ionic equation for the reaction with the greatest thermodynamic favorability. In part (f)(ii) the point was not earned because the E°_{cell} calculated does not represent the reaction with the greatest thermodynamic favorability and is inconsistent with part (f)(i). In part (f)(iii) the point was not earned because although the E°_{cell} is consistent with part (f)(ii), the calculation of ΔG° uses an incorrect n value that is inconsistent with part (f)(i). In part (f)(iv) the point was not earned because the response agrees that the mass decreases.