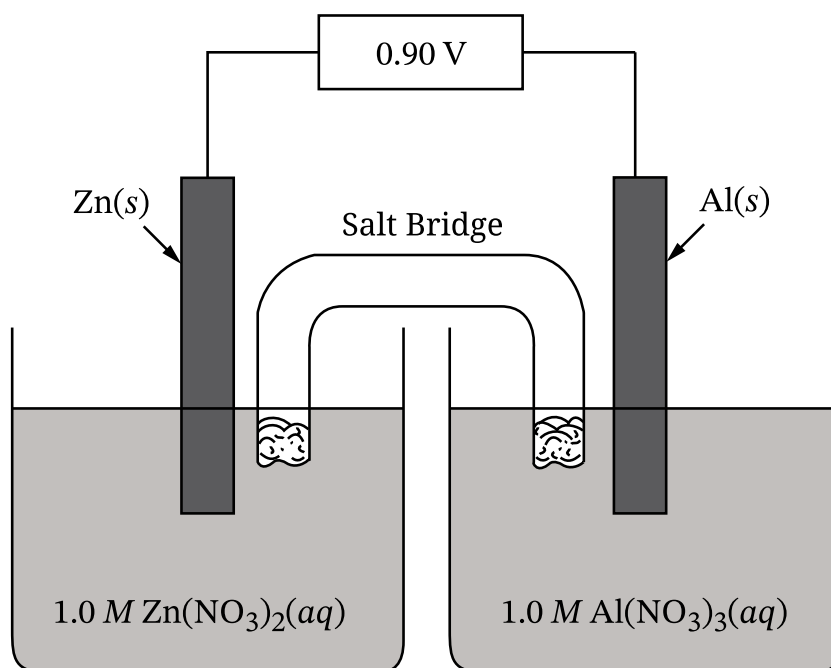


6. A scientist constructs a galvanic cell as shown in the diagram. As the cell operates, the $\text{Zn}(s)$ electrode increases in mass and the $\text{Al}(s)$ electrode decreases in mass. A data table with the standard reduction potentials for the substances follows the diagram.



Half-Reaction	E° (V)
$\text{Zn}^{2+}(aq) + 2e^- \rightarrow \text{Zn}(s)$	-0.76
$\text{Al}^{3+}(aq) + 3e^- \rightarrow \text{Al}(s)$	-1.66

- A. Write the half-reaction for the oxidation that occurs at the anode.
- B. Write the balanced net ionic equation for the overall reaction that occurs in the galvanic cell.
- C. Initially, each electrode has a mass of 50.0 g. The cell is allowed to run for a period of time and is then stopped. Which electrode's mass changed the most? Justify your answer with a calculation.

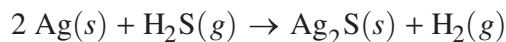
AP CHEMISTRY 2025 FREE-RESPONSE QUESTIONS

Reduction Half-Reaction	E° (V)
$\text{Au}^{3+}(aq) + 3e^- \rightarrow \text{Au}(s)$	+1.50
$\text{Zn}^{2+}(aq) + 2e^- \rightarrow \text{Zn}(s)$	-0.76
$\text{Mn}^{2+}(aq) + 2e^- \rightarrow \text{Mn}(s)$	-1.19
$\text{Al}^{3+}(aq) + 3e^- \rightarrow \text{Al}(s)$	-1.66
$\text{Be}^{2+}(aq) + 2e^- \rightarrow \text{Be}(s)$	-1.85

- D. The standard Zn/Al cell has a value of E°_{cell} equal to 0.90 V. The scientist needs a galvanic cell that produces a greater voltage. The scientist has access to the chemical systems in the table. If the scientist uses the Zn half-cell and one of the other options from the table, what is the MAXIMUM voltage that could be generated at standard conditions?

Begin your response to **QUESTION 3** on this page.

3. Sterling silver is an alloy that is commonly used to make jewelry and consists of 92.5% silver and 7.5% other metals, such as copper, by mass. Over time, the alloy can form a tarnish of $\text{Ag}_2\text{S}(s)$ when it reacts with hydrogen sulfide, as represented by the following equation.



- (a) What are the oxidation numbers of silver in $\text{Ag}(s)$ and $\text{Ag}_2\text{S}(s)$?

$\text{Ag}(s)$ _____ $\text{Ag}_2\text{S}(s)$ _____

- (b) The following table contains the atomic radii for silver and copper.

Element	Silver (Ag)	Copper (Cu)
Atomic radius (pm)	165	145

- (i) Explain why sterling silver is better classified as a substitutional alloy than as an interstitial alloy.
- (ii) Using principles of atomic structure and Coulomb's law, explain why silver has a larger atomic radius than copper does.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

The Ag_2S tarnish on sterling silver can be removed until only sterling silver remains. A student weighs a tarnished sterling silver sample both before and after removing the $\text{Ag}_2\text{S}(s)$ (molar mass 247.80 g/mol) and records the data in the following table.

	Before Tarnish Removal	After Tarnish Removal
Mass	409.21 g	398.94 g

(c) Assuming that only $\text{Ag}_2\text{S}(s)$ is removed, calculate the number of moles of silver atoms removed.

Rhodium plating is a process used to protect sterling silver from tarnishing. This involves electroplating (depositing) solid rhodium, $\text{Rh}(s)$, onto the surface of the metal from an acidified solution of $\text{Rh}_2(\text{SO}_4)_3(aq)$. Oxygen gas is produced during this process.

(d) A table of half-reactions related to the overall reaction is provided.

Half-Reaction	E° (V)
$\text{Rh}^{3+}(aq) + 3 e^- \rightarrow \text{Rh}(s)$	+0.80
$\text{O}_2(g) + 4 \text{H}^+(aq) + 4 e^- \rightarrow 2 \text{H}_2\text{O}(l)$	+1.23

(i) Write the balanced net ionic equation for plating $\text{Rh}(s)$ from the acidified $\text{Rh}_2(\text{SO}_4)_3(aq)$ solution.

(ii) Calculate the value of E_{cell}° for the reaction in part (d)(i).

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

(iii) Based on your answer to part (d)(ii), explain why this process requires the use of an external power source.

(e) Calculate the length of time, in seconds, required to plate 2.8 g of Rh(s) onto a piece of sterling silver if 2.0 C / s of current is applied.

GO ON TO THE NEXT 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.

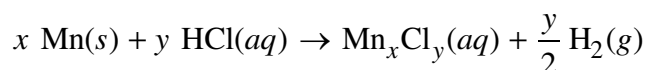
1. Answer the following questions related to manganese compounds.

(a) Manganese has several common oxidation states.

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

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

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

**GO ON TO THE NEXT PAGE.**

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

The student heats the resulting mixture until only $\text{Mn}_x\text{Cl}_y(s)$ remains in the beaker. The data are given in the following table.

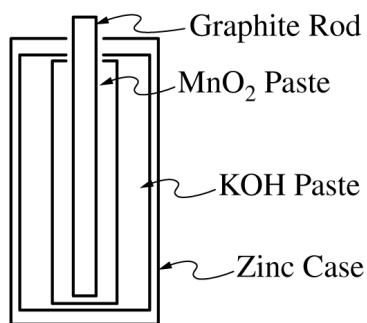
Mass of empty beaker	60.169 g
Mass of beaker and $\text{Mn}(s)$	61.262 g
Mass of beaker and Mn_xCl_y after heating to constant mass	62.673 g

- (b) Calculate the mass of Cl in the sample of $\text{Mn}_x\text{Cl}_y(s)$ remaining in the beaker.
- (c) Calculate the number of moles of Cl in the sample of $\text{Mn}_x\text{Cl}_y(s)$ remaining in the beaker.
- (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 $\text{Mn}_x\text{Cl}_y(s)$.
- (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.

GO ON TO THE NEXT PAGE.

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)
$\text{Zn}^{2+}(aq) + 2 e^- \rightarrow \text{Zn}(s)$	-0.76
$\text{ZnO}(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{Zn}(s) + 2 \text{OH}^-(aq)$	-1.28
$2 \text{MnO}_2(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{Mn}_2\text{O}_3(s) + 2 \text{OH}^-(aq)$	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.

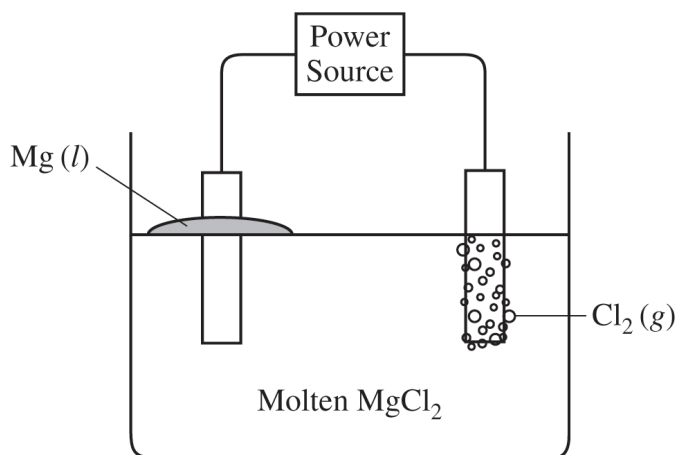
- (ii) Calculate the value of E°_{cell} for the overall reaction.

- (iii) Calculate the value of ΔG° in $\text{kJ/mol}_{\text{rxn}}$.

- (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.

GO ON TO THE NEXT PAGE.

Begin your responses to questions on this page.



Half-Reaction	E° (V)
$\text{Mg}^{2+} + 2 e^- \rightarrow \text{Mg}$	-2.37
$\text{Cl}_2 + 2 e^- \rightarrow 2 \text{Cl}^-$	+1.36

- i. Molten MgCl_2 can be decomposed into its elements if a sufficient voltage is applied using inert electrodes. The products of the reaction are liquid Mg (at the cathode) and Cl_2 gas (at the anode). A simplified representation of the cell is shown above. The reduction half-reactions related to the overall reaction in the cell are given in the table.

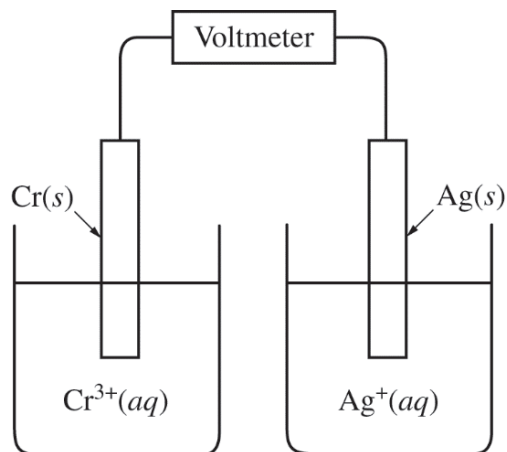
(a) Draw an arrow on the diagram to show the direction of electron flow through the external circuit as the cell operates.

(b) Would an applied voltage of 2.0 V be sufficient for the reaction to occur? Support your claim with a calculation as part of your answer.

(c) If the current in the cell is kept at a constant 5.00 amps, how many seconds does it take to produce 2.00 g of $\text{Mg}(l)$ at the cathode?

GO ON TO THE NEXT PAGE.

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



6. A student sets up a galvanic cell at 298 K that has an electrode of $\text{Ag}(s)$ immersed in a 1.0 M solution of $\text{Ag}^+(aq)$ and an electrode of $\text{Cr}(s)$ immersed in a 1.0 M solution of $\text{Cr}^{3+}(aq)$, as shown in the diagram above.
- (a) The student measures the voltage of the cell shown above and discovers that it is zero. Identify the missing component of the cell, and explain its importance for obtaining a nonzero voltage.

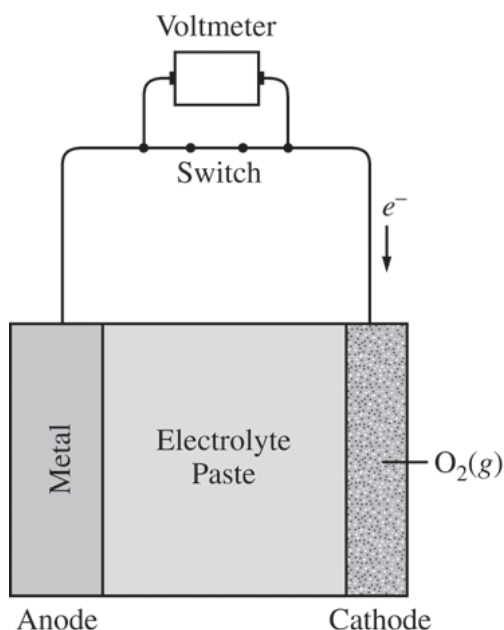
Half-Reaction	E° (V)
$\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s)$	+ 0.80
$\text{Cr}^{3+}(aq) + 3 e^- \rightarrow \text{Cr}(s)$	?

- (b) The student adds the missing component to the cell and measures E°_{cell} to be +1.54 V. As the cell operates, Ag^+ ions are reduced. Use this information and the information in the table above to do the following.
- Calculate the value of E° for the half-reaction $\text{Cr}^{3+}(aq) + 3 e^- \rightarrow \text{Cr}(s)$.
 - Write the balanced net-ionic equation for the overall reaction that occurs as the cell operates.
 - Calculate the value of ΔG° for the overall cell reaction in $\text{J/mol}_{\text{rxn}}$.

CHEMISTRY**Section II****7 Questions****Time—1 hour and 45 minutes****YOU MAY USE YOUR CALCULATOR FOR THIS SECTION.**

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.

Write your response in the space provided following each question. 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.



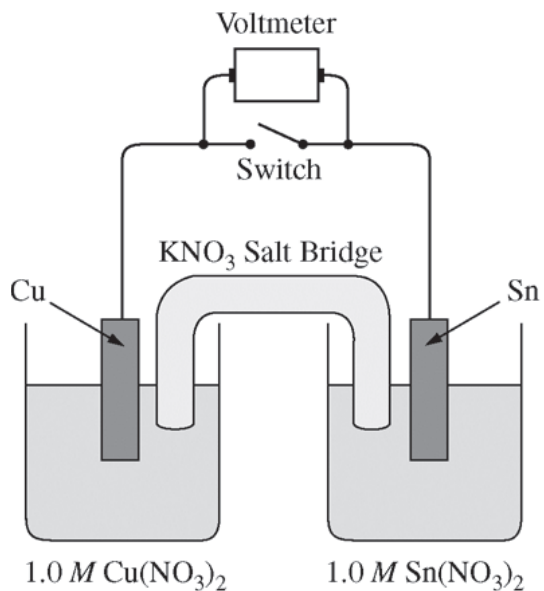
1. Metal-air cells are a relatively new type of portable energy source consisting of a metal anode, an alkaline electrolyte paste that contains water, and a porous cathode membrane that lets in oxygen from the air. A schematic of the cell is shown above. Reduction potentials for the cathode and three possible metal anodes are given in the table below.

Half Reaction	E at pH 11 and 298 K (V)
$\text{O}_2(g) + 2 \text{H}_2\text{O}(l) + 4 e^- \rightarrow 4 \text{OH}^-(aq)$	+0.34
$\text{ZnO}(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{Zn}(s) + 2 \text{OH}^-(aq)$	–1.31
$\text{Na}_2\text{O}(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow 2 \text{Na}(s) + 2 \text{OH}^-(aq)$	–1.60
$\text{CaO}(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{Ca}(s) + 2 \text{OH}^-(aq)$	–2.78

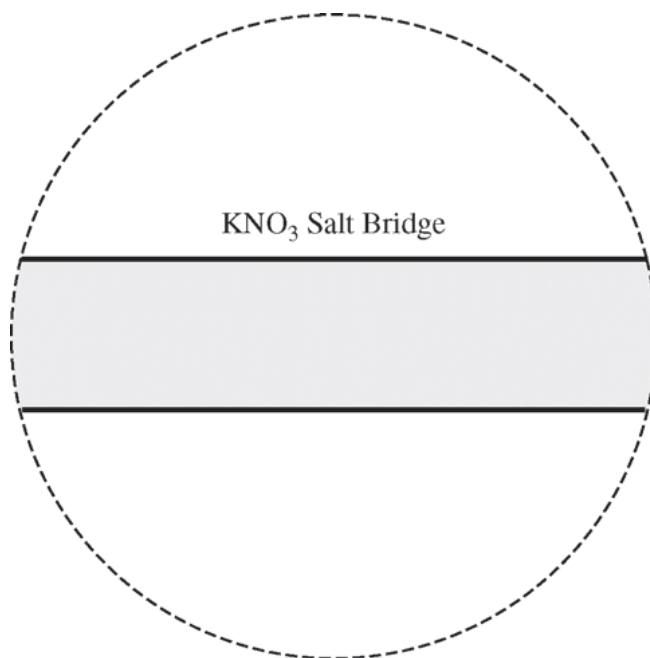
- (a) Early forms of metal-air cells used zinc as the anode. Zinc oxide is produced as the cell operates according to the overall equation below.



- (i) Using the data in the table above, calculate the cell potential for the zinc-air cell.
- (ii) The electrolyte paste contains OH^- ions. On the diagram of the cell above, draw an arrow to indicate the direction of migration of OH^- ions through the electrolyte as the cell operates.
- (b) A fresh zinc-air cell is weighed on an analytical balance before being placed in a hearing aid for use.
- (i) As the cell operates, does the mass of the cell increase, decrease, or remain the same?
- (ii) Justify your answer to part (b)(i) in terms of the equation for the overall cell reaction.
- (c) The zinc-air cell is taken to the top of a mountain where the air pressure is lower.
- (i) Will the cell potential be higher, lower, or the same as the cell potential at the lower elevation?
- (ii) Justify your answer to part (c)(i) based on the equation for the overall cell reaction and the information above.
- (d) Metal-air cells need to be lightweight for many applications. In order to transfer more electrons with a smaller mass, Na and Ca are investigated as potential anodes. A 1.0 g anode of which of these metals would transfer more electrons, assuming that the anode is totally consumed during the lifetime of a cell? Justify your answer with calculations.
- (e) The only common oxide of zinc has the formula ZnO .
- (i) Write the electron configuration for a Zn atom in the ground state.
- (ii) From which sublevel are electrons removed when a Zn atom in the ground state is oxidized?



3. A student is given a standard galvanic cell, represented above, that has a Cu electrode and a Sn electrode. As current flows through the cell, the student determines that the Cu electrode increases in mass and the Sn electrode decreases in mass.
- (a) Identify the electrode at which oxidation is occurring. Explain your reasoning based on the student's observations.
- (b) As the mass of the Sn electrode decreases, where does the mass go?
- (c) In the expanded view of the center portion of the salt bridge shown in the diagram below, draw and label a particle view of what occurs in the salt bridge as the cell begins to operate. Omit solvent molecules and use arrows to show the movement of particles.



- (d) A nonstandard cell is made by replacing the 1.0 *M* solutions of $\text{Cu}(\text{NO}_3)_2$ and $\text{Sn}(\text{NO}_3)_2$ in the standard cell with 0.50 *M* solutions of $\text{Cu}(\text{NO}_3)_2$ and $\text{Sn}(\text{NO}_3)_2$. The volumes of solutions in the nonstandard cell are identical to those in the standard cell.
- Is the cell potential of the nonstandard cell greater than, less than, or equal to the cell potential of the standard cell? Justify your answer.
 - Both the standard and nonstandard cells can be used to power an electronic device. Would the nonstandard cell power the device for the same time, a longer time, or a shorter time as compared with the standard cell? Justify your answer.
- (e) In another experiment, the student places a new Sn electrode into a fresh solution of 1.0 *M* $\text{Cu}(\text{NO}_3)_2$.

Half-Reaction	E° (V)
$\text{Cu}^+ + e^- \rightarrow \text{Cu}(s)$	0.52
$\text{Cu}^{2+} + 2 e^- \rightarrow \text{Cu}(s)$	0.34
$\text{Sn}^{4+} + 2 e^- \rightarrow \text{Sn}^{2+}$	0.15
$\text{Sn}^{2+} + 2 e^- \rightarrow \text{Sn}(s)$	-0.14

- Using information from the table above, write a net-ionic equation for the reaction between the Sn electrode and the $\text{Cu}(\text{NO}_3)_2$ solution that would be thermodynamically favorable. Justify that the reaction is thermodynamically favorable.
- Calculate the value of ΔG° for the reaction. Include units with your answer.