Question 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)
$O_2(g) + 2 H_2O(l) + 4 e^- \rightarrow 4 OH^-(aq)$	+0.34
$ZnO(s) + H_2O(l) + 2 e^- \rightarrow Zn(s) + 2 OH^-(aq)$	−1.31
$Na_2O(s) + H_2O(l) + 2 e^- \rightarrow 2 Na(s) + 2 OH^-(aq)$	−1.60
$CaO(s) + H_2O(l) + 2 e^- \rightarrow Ca(s) + 2 OH^-(aq)$	−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.

$$2 Zn(s) + O_2(g) \rightarrow 2 ZnO(s)$$
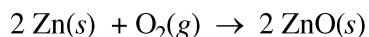
    (i) Using the data in the table above, calculate the cell potential for the zinc-air cell.

$E_{cell} = 0.34 \text{ V} - (-1.31 \text{ V}) = 1.65 \text{ V}$	1 point is earned for the correct cell potential.

    (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.

(The arrow should point to the left.)	1 point is earned for indicating the movement of OH^- ions from right to left in the cell.

(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?

The mass increases.	1 point is earned for indicating an increase in cell mass.

    (ii) Justify your answer to part (b)(i) in terms of the equation for the overall cell reaction.

Oxygen gas from the air reacts with $Zn(s)$ in the cell, producing $ZnO(s)$, which has more mass than the original $Zn(s)$.	1 point is earned for the justification.

(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?

The cell potential will be lower.	1 point is earned for indicating a lower cell potential.

    (ii) Justify your answer to part (c)(i) based on the equation for the overall cell reaction and the information above.

$O_2(g)$, a reactant in the cell reaction, will be at a lower partial pressure at the higher elevation; thus the reaction has a greater value of Q (closer to K). Deviations in partial pressure that take the cell closer to equilibrium will decrease the magnitude of the cell potential.	1 point is earned for a justification that relates a lower pressure (or concentration) of $O_2(g)$ to Q, or a qualitative approach using the Nernst equation.

(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.

For Na, $1.0 \text{ g Na} \times \dfrac{1.0 \text{ mol Na}}{22.99 \text{ g Na}} \times \dfrac{1.0 \text{ mol } e^-}{1.0 \text{ mol Na}} = 0.043 \text{ mol } e^-$ For Ca, $1.0 \text{ g Ca} \times \dfrac{1.0 \text{ mol Ca}}{40.08 \text{ g Ca}} \times \dfrac{2.0 \text{ mol } e^-}{1.0 \text{ mol Ca}} = 0.050 \text{ mol } e^-$ The cell with the Ca anode would transfer more electrons.	1 point is earned for the correct calculation of moles for Na and Ca. 1 point is earned for taking 1 vs. 2 moles of electrons into account and the correct answer.

(e) The only common oxide of zinc has the formula ZnO.

    (i) Write the electron configuration for a Zn atom in the ground state.

$1s^2\ 2s^2\, 2p^6\ 3s^2\, 3p^6\ 4s^2\, 3d^{10}$ or [Ar] $4s^2\, 3d^{10}$	1 point is earned for a correct configuration.

    (ii) From which sublevel are electrons removed when a Zn atom in the ground state is oxidized?

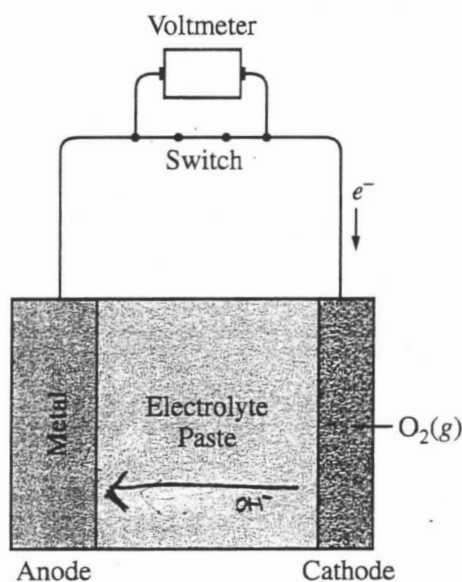| $4s$ sublevel	1 point is earned for the correct answer.

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.
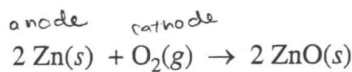

1. Metal-air cells are a relatively new type of portable energy source consisting of a metal anode, an alkaline electrolyte paste that contains water, and a porous cathode membrane that lets in oxygen from the air. A schematic of the cell is shown above. Reduction potentials for the cathode and three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

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$Na_2O(s) + H_2O(l) + 2\,e^- \rightarrow 2\,Na(s) + 2\,OH^-(aq)$	−1.60
$CaO(s) + H_2O(l) + 2\,e^- \rightarrow Ca(s) + 2\,OH^-(aq)$	−2.78

GO ON TO THE NEXT PAGE.

(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.

anode   cathode

$$2 Zn(s) + O_2(g) \rightarrow 2 ZnO(s)$$

   (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?

a)(i) $E°_{cell} = E°_{cathode} - E°_{anode} = 0.34 V - (-1.31 V) = \boxed{1.65 V}$

b) (i) increase

   (ii) ZnO is being created which increases the mass as oxygen reacts w/ Zn metal

c)(i) lower

   (ii) at a higher elevation there is less oxygen so P_{oxygen} is lower. This decreases E_{cell} based on the Nerst equation $E_{cell} = E°_{cell} - \frac{0.0592}{n} \log Q$ where $Q = \frac{1}{P_{O_2}}$ and Q increases at higher elevation, so E_{cell} decreases

d) $\frac{1g\ Na}{22.99\ g/mol} = 0.0435\ mol\ Na \times \frac{4\ mol\ e^-}{4\ mol\ Na} = 0.0435\ mol\ e^-$ transferred

$$4 Na + O_2 \rightarrow 2 Na_2O \quad n=4$$

$\frac{1g\ Ca}{40.08\ g/mol} = 0.025\ mol\ Ca \times \frac{4\ mol\ e^-}{2\ mol\ Ca} = 0.0500\ mol\ e^-$ transferred

$$2 Ca + O_2 \rightarrow 2 CaO \quad n=4$$

1g $\boxed{Ca}$ transfers more electrons

GO ON TO THE NEXT PAGE.

e) (i) $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10}$

(ii) from the 4s sublevel
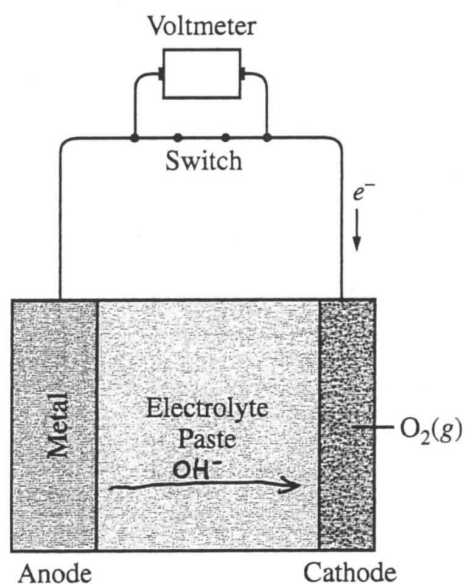
CHEMISTRY
Section II
7 Questions
Time—1 hour and 45 minutes

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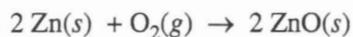

1. Metal-air cells are a relatively new type of portable energy source consisting of a metal anode, an alkaline electrolyte paste that contains water, and a porous cathode membrane that lets in oxygen from the air. A schematic of the cell is shown above. Reduction potentials for the cathode and three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

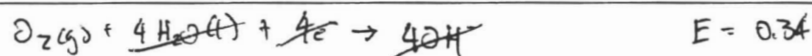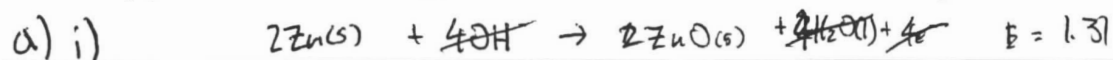| Half Reaction	E at pH 11 and 298 K (V)
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$CaO(s) + H_2O(l) + 2\,e^- \rightarrow Ca(s) + 2\,OH^-(aq)$	−2.78

GO ON TO THE NEXT PAGE.

(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.

$$2\,Zn(s) + O_2(g) \rightarrow 2\,ZnO(s)$$

   (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?

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a) i) $2Zn(s) + 4OH^- \rightarrow 2ZnO(s) + 2H_2O(l) + 4e^-$ $E = 1.31$

             $O_2(g) + 4H_2O(l) + 4e^- \rightarrow 4OH^-$ $E = 0.34$

                           $E_{cell} = E_{anode} + E_{cathode}$ $1.31 + 0.34 = \boxed{1.65\ V}$
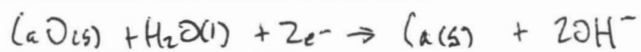
ii)

b) i) increase

ii) oxygen from the surroundings is being reacted with the Zn(s) in the system to form ZnO(s), therefore mass increases

c) i) lower

ii) $PV = nRT$ when pressure is lowered, so is the number of moles of oxygen. Since there is less oxygen, the equation shifts to the left due to le Chatelier's principle and thus the cell potential is lower
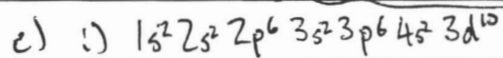
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d) $Na_2O(s) + H_2O(l) + 2e^- \rightarrow 2Na(s) + 2OH^-(aq)$
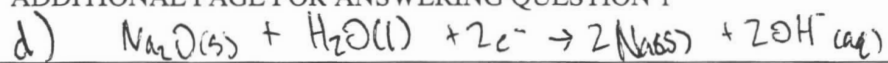
$1.0g\ Na \times \dfrac{1\ mol\ Na}{22.99g} \times \dfrac{2\ mol\ e^-}{2\ mol\ Na} = 0.043\ mol\ e^-$

$CaO(s) + H_2O(l) + 2e^- \rightarrow Ca(s) + 2OH^-$

$1.0g\ Ca \times \dfrac{1\ mol\ Ca}{40.08g} \times \dfrac{2\ mol\ e^-}{1\ mol\ Ca} = 0.050\ mol\ e^-$

Ca would transfer more electrons

e) i) $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10}$

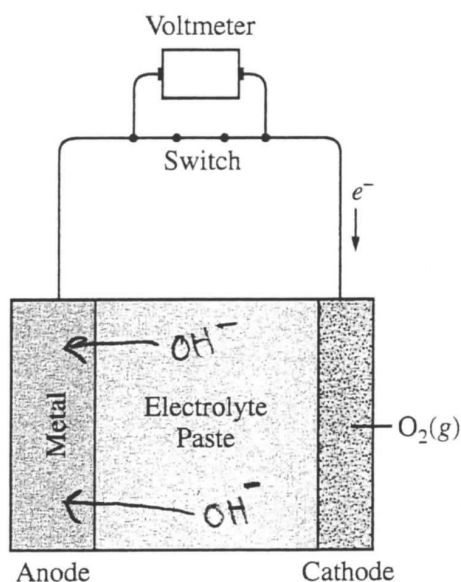ii) the 4s sublevel

CHEMISTRY

Section II

7 Questions

Time—1 hour and 45 minutes

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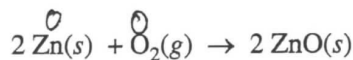

1. Metal-air cells are a relatively new type of portable energy source consisting of a metal anode, an alkaline electrolyte paste that contains water, and a porous cathode membrane that lets in oxygen from the air. A schematic of the cell is shown above. Reduction potentials for the cathode and three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

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GO ON TO THE NEXT PAGE.

-6-

(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.

$$2\,\overset{O}{Zn}(s) + \overset{O}{O_2}(g) \rightarrow 2\,ZnO(s)$$

   (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?

(a)(i) $E_{cell} = E_{cathode} - E_{anode}$

Cathode is where reduction occurs (O_2)

Anode is where oxidation occurs (metal)

Thus for the zinc-air cell the potential is:

$0.34V - (-1.31V) = 1.65V$

(ii) see diagram

(b)(i) The mass of the cell remains the same

(ii) In the overall cell reaction, there is conservation of mass. The equation for the overall cell reaction: $2Zn(s) + O_2(g) \rightarrow 2ZnO(s)$ possess the same number and types of atoms. Also, the electrons transferred in the cell are effectively counted in the equation, thus the mass remains unchanged in the reaction

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-7-

c (i) (ii) The cell potential will be lower because the cell relies on oxygen supplied by the air. At higher elevations there is less oxygen present in the air. Thus according to Le Chatelier's principle for the half-reaction $O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$, it will be less likely for O_2 to be reduced in response to the reduction in its concentration at a higher altitude. Le Chatelier's principle is also reflected with the overall cell reaction $2Zn(s) + O_2(g) \rightarrow 2ZnO(s)$ with less O_2 present, there will be less ZnO formed, which reduces the cell's overall potential
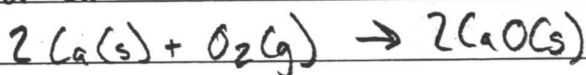
d. For Na:

$$4Na(s) + O_2(g) \rightarrow 2Na_2O$$
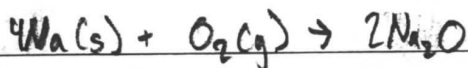
~~Potential of this cell: 0.34V - (-1.60V) = 1.94V~~

Na has 1 valence electron so for every mol of $Na(s)$ in reaction, there is 1 mol of electrons transferred.

$1.0 g\ Na \cdot \dfrac{1 mol\ Na}{22.99 g} \cdot 4\ moles^{Na}(in\ formula) \cdot \dfrac{1\ mol\ electrons}{1\ mol\ Na} = 0.17\ mol\ electrons$
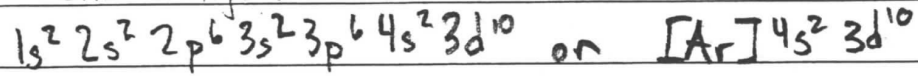
For Ca:

$$2Ca(s) + O_2(g) \rightarrow 2CaO(s)$$

Ca has 2 valence electrons, so for every mol of $Ca(s)$ in reaction, there are 2 mol of electrons transferred

$1.0 g\ Ca \cdot \dfrac{1 mol\ Ca}{40.08 g} \cdot 2 mol\ Ca\ (in\ equation) \cdot \dfrac{2\ mol\ electrons}{1 mol\ Ca} = 0.010\ mol\ electrons$

The anode of $Na(s)$ would transfer more electrons

(e)(i) Zinc configuration:

$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10}$ or $[Ar] 4s^2 3d^{10}$

(ii) When zinc is oxidised, it loses its electrons from the 4s sublevel, where it has 2 electrons

AP® CHEMISTRY
2015 SCORING COMMENTARY

Question 1

Overview

Question 1 assessed students' understanding of electrochemistry and its relationship to concepts from thermodynamics, equilibrium, and atomic structure. Students were asked a series of questions about a metal-air cell, a relatively modern type of portable energy source, which represents a real world application of chemistry.

Sample: 1A
Score: 10

This response was well-crafted and earned full credit. Two points were earned in part (a) because the cell potential is correctly calculated, and the prediction of OH^- anion flow in the direction of the anode is correct. In part (b) the response predicts an increase in cell mass and justifies that choice to earn 2 points. In part (c) both points were earned because the response correctly predicts a lower cell potential and explains the change by describing the ratio Q. In part (d) 1 point was earned for converting 1.0 g masses of sodium and calcium metals to moles and another point was earned for then calculating the number of moles of electrons transferred in each case and then selecting calcium metal as the preferred metal anode. In part (e) 2 points were earned because the response offers the correct electron configuration and selects the $4s$ sublevel as the source of electrons to be removed from the zinc atom.

Sample: 1B
Score: 8

One point was earned in part (a)(i) for calculating the correct cell potential for the metal-air cell. No point was earned in part (a)(ii) because the direction of anion flow across the electrolytic paste (toward the anode) is not correctly predicted. In part (b) both points were earned for stating that the cell mass will increase and for the rationale. Part (c) earned 1 of 2 points because the prediction is correct, but the LeChâtelier argument is not. In part (d) 1 point was earned for finding the number of moles of sodium and calcium. The response's justification of calcium as the preferred metal in terms of electrons transferred is correct for another point. Part (e) earned both points for a correct electron configuration and correct prediction that the valence $4s$ electrons will be removed from the zinc atom to form the Zn^{2+} cation.

Sample: 1C
Score: 6

This response earned both points in part (a). No points were earned in part (b) for an incorrect choice of the mass remaining the same and an incorrect explanation. In part (c) 1 point was earned for predicting a lower potential but the explanation, using LeChâtelier's Principle, is not adequate. In part (d) 1 point was earned for calculating the number of moles of possible anode metal but the second point was not earned because sodium is selected. Part (e) shows the correct electron configuration and predicts which electrons will be removed, and 2 points were earned.