2. Answer the following questions involving the stoichiometry and thermodynamics of reactions containing aluminum species.

$$2\ Al_2O_3(l) + 3\ C(s) \rightarrow 4\ Al(l) + 3\ CO_2(g)$$

An electrolytic cell produces 235 g of Al(*l*) according to the equation above.

(a) Calculate the number of moles of electrons that must be transferred in the cell to produce the 235 g of Al(*l*).

(b) A steady current of 152 amp was used during the process. Determine the amount of time, in seconds, that was needed to produce the Al(*l*).

(c) Calculate the volume of $CO_2(g)$, measured at 301 K and 0.952 atm, that is produced in the process.

(d) For the electrolytic cell to operate, the Al_2O_3 must be in the liquid state rather than in the solid state. Explain.

When Al(*s*) is placed in a concentrated solution of KOH at 25°C, the reaction represented below occurs.

$$2\ Al(s) + 2\ OH^-(aq) + 6\ H_2O(l) \rightarrow 2[Al(OH)_4]^-(aq) + 3\ H_2(g)$$

Half-reaction	$E°$ (V)
$[Al(OH)_4]^-(aq) + 3\ e^- \rightarrow Al(s) + 4\ OH^-(aq)$	−2.35
$2\ H_2O(l) + 2\ e^- \rightarrow H_2(g) + 2\ OH^-(aq)$	−0.83

(e) Using the table of standard reduction potentials shown above, calculate the following.

(i) $E°$, in volts, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

(ii) $\Delta G°$, in kJ/mol_{rxn}, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

GO ON TO THE NEXT PAGE.

Question 2

Answer the following questions involving the stoichiometry and thermodynamics of reactions containing aluminum species.

$$2\ Al_2O_3(l) + 3\ C(s) \rightarrow 4\ Al(l) + 3\ CO_2(g)$$

An electrolytic cell produces 235 g of Al(l) according to the equation above.

(a) Calculate the number of moles of electrons that must be transferred in the cell to produce the 235 g of Al(l).

$235 \text{ g Al} \times \dfrac{1 \text{ mol Al}}{26.98 \text{ g Al}} = 8.71 \text{ mol Al}$ $Al^{3+} + 3\,e^- \rightarrow Al$, therefore, 3 mol e^- transferred per mol Al $8.71 \text{ mol Al} \times \dfrac{3 \text{ mol } e^-}{1 \text{ mol Al}} = 26.1 \text{ mol } e^-$	1 point is earned for the number of moles of Al. 1 point is earned for correct stoichiometry and the number of moles of electrons.

(b) A steady current of 152 amp was used during the process. Determine the amount of time, in seconds, that was needed to produce the Al(l).

charge $=$ moles $e^- \times$ Faraday's constant $= 26.1 \text{ mol } e^- \times \dfrac{9.65 \times 10^4 \text{ C}}{1 \text{ mol } e^-} = 2.52 \times 10^6 \text{ C}$	1 point is earned for the correct amount of charge transferred.
$I = \dfrac{q}{t}$ $t = \dfrac{q}{I} = \dfrac{2.52 \times 10^6 \text{ C}}{152 \text{ C/s}} = 1.66 \times 10^4 \text{ s}$	1 point is earned for the correct time.

(c) Calculate the volume of $CO_2(g)$, measured at 301 K and 0.952 atm, that is produced in the process.

$\text{mol } CO_2 = 8.71 \text{ mol Al} \times \dfrac{3 \text{ mol } CO_2}{4 \text{ mol Al}} = 6.53 \text{ mol } CO_2$	1 point is earned for the number of moles of CO_2.
$PV = nRT$ $V = \dfrac{nRT}{P} = \dfrac{(6.53 \text{ mol})\left(0.0821 \dfrac{\text{L atm}}{\text{mol K}}\right)(301 \text{ K})}{0.952 \text{ atm}} = 1.70 \times 10^2 \text{ L } CO_2$	1 point is earned for the volume of CO_2.

Question 2 (continued)

(d) For the electrolytic cell to operate, the Al_2O_3 must be in the liquid state rather than in the solid state. Explain.

Al_2O_3 is an ionic compound; in the solid state it will not conduct electricity. In order for the cell to operate, Al_2O_3 must be in the liquid state so that the ions are mobile and able to move to the electrodes to react (and/or complete the circuit).	1 point is earned for a correct explanation.

When Al(*s*) is placed in a concentrated solution of KOH at 25°C, the reaction represented below occurs.

$$2\ Al(s)\ +\ 2\ OH^-(aq)\ +\ 6\ H_2O(l)\ \rightarrow\ 2[Al(OH)_4]^-(aq)\ +3\ H_2(g)$$

Half-reaction	$E°$ (V)
$[Al(OH)_4]^-(aq)\ +\ 3\ e^-\ \rightarrow\ Al(s) +\ 4\ OH^-(aq)$	–2.35
$2\ H_2O(l)\ +\ 2\ e^-\ \rightarrow\ H_2(g)\ +\ 2\ OH^-(aq)$	–0.83

(e) Using the table of standard reduction potentials shown above, calculate the following.

(i) $E°$, in volts, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

$E° = E°_{cathode} - E°_{anode} = -0.83\ V - (-2.35\ V) = 1.52\ V$	1 point is earned for the correct value of $E°$.

(ii) $\Delta G°$, in kJ/mol_{rxn}, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

$\Delta G° = -nFE° = -(6)(9.65 \times 10^4\ C)(1.52\ V)$ $= -8.80 \times 10^5\ J/mol_{rxn} = -8.80 \times 10^2\ kJ/mol_{rxn}$ (or $-880.\ kJ/mol_{rxn}$)	1 point is earned for $n = 6$. 1 point is earned for the correct value of $\Delta G°$.

2A 1

2. Answer the following questions involving the stoichiometry and thermodynamics of reactions containing aluminum species.

$$2\,Al_2O_3(l) + 3\,C(s) \rightarrow 4\,Al(l) + 3\,CO_2(g)$$

An electrolytic cell produces 235 g of Al(l) according to the equation above.

(a) Calculate the number of moles of electrons that must be transferred in the cell to produce the 235 g of Al(l).

(b) A steady current of 152 amp was used during the process. Determine the amount of time, in seconds, that was needed to produce the Al(l).

(c) Calculate the volume of $CO_2(g)$, measured at 301 K and 0.952 atm, that is produced in the process.

(d) For the electrolytic cell to operate, the Al_2O_3 must be in the liquid state rather than in the solid state. Explain.

When Al(s) is placed in a concentrated solution of KOH at 25°C, the reaction represented below occurs.

$$2\,Al(s) + 2\,OH^-(aq) + 6\,H_2O(l) \rightarrow 2[Al(OH)_4]^-(aq) + 3\,H_2(g)$$

Half-reaction	$E°$ (V)
$[Al(OH)_4]^-(aq) + 3\,e^- \rightarrow Al(s) + 4\,OH^-(aq)$	−2.35
$2\,H_2O(l) + 2\,e^- \rightarrow H_2(g) + 2\,OH^-(aq)$	−0.83

(e) Using the table of standard reduction potentials shown above, calculate the following.

(i) $E°$, in volts, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

(ii) $\Delta G°$, in kJ/mol$_{rxn}$, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

2)a) half reaction: $12e^- + 12H^+ + 2Al_2O_3 \rightarrow 4Al + 6H_2O$
8.71

$235\,g\,Al \times \frac{1\,mol}{26.98\,g} = 8.71\,mol\,Al$

$(8.71\,mol\,Al)\left(\frac{12\,mol\,e^-}{4\,mol\,Al}\right) = 26.1\,mol\,e^-$

b) $(26.1\,mol\,e^-)\left(\frac{96{,}500\,C}{1\,mol\,e^-}\right) = 2.52\times10^6\,C$

$I = \frac{q}{t} \rightarrow t = q/I = \frac{2.52\times10^6\,C}{152\,amp} = 1.66\times10^4$ seconds

$t =$ 2.5

(see next page)

2A2

c) $(8.71 \text{ mol Al})\left(\frac{3 \text{ mol } CO_2}{4 \text{ mol Al}}\right) = 6.53 \text{ mol } CO_2$

$PV = nRT \rightarrow V = \frac{nRT}{P} = \frac{(6.53 \text{ mol})(.0821 \frac{L \cdot atm}{mol \cdot K})(301 \text{ K})}{.952 \text{ atm}} = \boxed{170. \text{ L}}$

d) - The cell only operates when Al_2O_3 contains free moving ions, because the Al^{3+} must be reduced to Al. This can only happen if the Al^{3+} is separated from the O^{2-}; the liquid state provides this, but the solid does not.
- In addition, the cell is an electrical circuit, and requires ions to be able to complete the circuit by carrying a charge.

e) i) $2Al + 8OH^- \rightarrow 2[Al(OH)_4]^- + 6e^-$ 2.35 V

$6H_2O + 6e^- \rightarrow 3H_2 + 6OH^-$ −0.83 V

$\boxed{1.52 \text{ V}}$

ii) $\Delta G^\circ = -nFE^\circ$

$= -(6 \text{ mol } e^-)\left(\frac{96{,}500 \text{ C}}{1 \text{ mol } e^-}\right)(1.52 \text{ V})\left(\frac{1 \text{ kJ}}{1000 \text{ J}}\right)$

$= \boxed{-880. \text{ kJ/mol}_{rxn}}$

GO ON TO THE NEXT PAGE.

2B 1

2. Answer the following questions involving the stoichiometry and thermodynamics of reactions containing aluminum species.

$$2\ Al_2O_3(l) + 3\ C(s) \rightarrow 4\ Al(l) + 3\ CO_2(g)$$

An electrolytic cell produces 235 g of Al(*l*) according to the equation above.

(a) Calculate the number of moles of electrons that must be transferred in the cell to produce the 235 g of Al(*l*).

(b) A steady current of 152 amp was used during the process. Determine the amount of time, in seconds, that was needed to produce the Al(*l*).

(c) Calculate the volume of $CO_2(g)$, measured at 301 K and 0.952 atm, that is produced in the process.

(d) For the electrolytic cell to operate, the Al_2O_3 must be in the liquid state rather than in the solid state. Explain.

When Al(*s*) is placed in a concentrated solution of KOH at 25°C, the reaction represented below occurs.

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Half-reaction	$E°$ (V)
$[Al(OH)_4]^-(aq) + 3\ e^- \rightarrow Al(s) + 4\ OH^-(aq)$	−2.35
$2\ H_2O(l) + 2\ e^- \rightarrow H_2(g) + 2\ OH^-(aq)$	−0.83

(e) Using the table of standard reduction potentials shown above, calculate the following.

(i) $E°$, in volts, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

(ii) $\Delta G°$, in kJ/mol$_{rxn}$, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

2(a) 235g Al · 1mol Al / 26.98g Al · 3mol e⁻ / 1mol Al = 26.1 mol e⁻

(b) 235g Al · 1mol Al / 26.98g Al · 3mol e⁻ / 1mol Al · 96,500 C / mol e⁻ · 1Amps / 1C · 1 / 152 Amps =

1.66×10⁴ seconds

(c) 235g Al · 1mol Al / 26.98g Al · 3mol CO₂ / 4mol Al = 6.53 mol CO₂

PV=nRT V=nRT/P

V = (6.53 mol)(0.0821 L atm / mol K)(301K) / 0.952 atm

V = 1730 L

GO ON TO THE NEXT PAGE.

2B2

d) Al_2O_3 must be in liquid state because in order for the electrolytic cell to work, the ions of the molecule must be able to move to some extent in order to conduct electricity. Solid Al_2O_3 would not allow this to happen.

e)

(i) $E^\circ_{cell} = 2.35 - 0.83 = \boxed{1.52V}$

(ii) $\Delta G^\circ = -nFE^\circ_{cell}$

$= -(6)\left(\frac{96500C}{mole^-}\right)(1.52V)$

$= -8.80 \times 10^5 \frac{KJ}{mol}$

GO ON TO THE NEXT PAGE.

2C1

2. Answer the following questions involving the stoichiometry and thermodynamics of reactions containing aluminum species.

$$2\,Al_2O_3(l) + 3\,C(s) \rightarrow 4\,Al(l) + 3\,CO_2(g)$$

An electrolytic cell produces 235 g of $Al(l)$ according to the equation above.

(a) Calculate the number of moles of electrons that must be transferred in the cell to produce the 235 g of $Al(l)$.

(b) A steady current of 152 amp was used during the process. Determine the amount of time, in seconds, that was needed to produce the $Al(l)$.

(c) Calculate the volume of $CO_2(g)$, measured at 301 K and 0.952 atm, that is produced in the process.

(d) For the electrolytic cell to operate, the Al_2O_3 must be in the liquid state rather than in the solid state. Explain.

When $Al(s)$ is placed in a concentrated solution of KOH at 25°C, the reaction represented below occurs.

$$2\,Al(s) + 2\,OH^-(aq) + 6\,H_2O(l) \rightarrow 2[Al(OH)_4]^-(aq) + 3\,H_2(g)$$

C - 6

Half-reaction	$E°$ (V)
$[Al(OH)_4]^-(aq) + 3\,e^- \rightarrow Al(s) + 4\,OH^-(aq)$	−2.35
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(e) Using the table of standard reduction potentials shown above, calculate the following.

Red (i) $E°$, in volts, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

(ii) $\Delta G°$, in kJ/mol$_{rxn}$, for the formation of $[Al(OH)_4]^-(aq)$ and $H_2(g)$ at 25°C

(a) ~~Al_2O~~ ① 235g × 1 mol / 26.98 g = 8.71 mols

$2Al_2^{3+} \rightarrow 4Al$

$2Al_2^{3+} + 3e^- \rightarrow 4Al$

② 3e⁻ / 1 mol × 8.71 mols = **26.1 mols e⁻**

(b) ② $2.52 \cdot 10^6$ C / Time = 152 amp ① 96,500 C × 26.1 mols e⁻ / mols e⁻ = $2.52 \cdot 10^6$ C

T = $1.66 \cdot 10^4$ seconds

GO ON TO THE NEXT PAGE

PV=nRT

2C2

(c) $V = \frac{n (0.0821)(574)}{0.952}$

(i) $\frac{3 CO_2}{4 Al} \cdot 8.71 \text{ mols Al} = $ (6.5325 mols CO_2)

$V = \frac{(6.5325)(0.0821)(574)}{0.952} = 323 L$

$3.23 \cdot 10^2 L$

(d) Al_2O_3 would have to be in liquid state rather than solid state because if it were in the solid state, the E_{cell} would be negative, making the reaction not ~~occur~~ happen.

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

$-0.83V + 2.35 = 1.52 V$

ii) $\Delta G = -nFE^0$

① · 2 → 6e⁻

· 3 → 6e⁻

$-12e (96,500)(1.52V) = -1760160$

$\Delta G = -1.76 \cdot 10^6 \text{ kJ/mols}$

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Question 2

Overview

This question assessed the students' ability to solve stoichiometry, electrochemistry, and thermodynamics problems and understand relationships between these concepts. Parts (a) through (d) involve answering questions about an electrolytic cell. In part (a) students calculated the number of moles of electrons transferred when a given mass of Al was produced in an electrolytic cell. Students used knowledge of stoichiometry and oxidation-reduction reactions to calculate this value. In part (b) students calculated the amount of time required to produce the Al in part (a) when given the current. This required an understanding of the concepts of charge and current. Part (c) asked students to calculate the volume of CO_2 gas produced in the process at a specific temperature and pressure. This part of the question assessed student understanding of stoichiometry and gas laws. Part (d) required students to explain the necessity for Al_2O_3 to be molten. This part evaluated students' understanding of ion mobility in an electrolytic cell. Part (e) asked students to calculate thermodynamic quantities for a different reaction. In part (e)(i) students calculated the value of $E°$ for the reaction using the table of standard reduction potentials. This assessed student understanding of half-cell potentials. In part (e)(ii) students calculated the standard free energy change for the reaction, demonstrating the ability to recognize total moles of electrons transferred and to apply an appropriate relationship between electrochemical and thermodynamic quantities.

Sample: 2A
Score: 10

This response earned all possible points. Part (a) earned 2 points; 1 point for the calculation of moles of Al and 1 point for multiplying the moles of Al by three moles of electrons transferred per mole of Al. Part (b) earned 2 points for calculating the amount of time needed to produce the Al; 1 point for calculating charge using the calculated moles of electrons from part (a) and 1 point for dividing the charge by the given current. Part (c) earned 2 points for calculating the volume of CO_2; 1 point for calculating the moles of CO_2 using the calculated moles of Al from part (a) and 1 point for correctly substituting in the ideal gas law equation and solving for volume. In part (d) 1 point was earned for indicating that ions are free to move in the cell and are necessary to complete the circuit. Part (e) earned 3 points total. In part (e)(i) 1 point was earned for calculating the voltage of the cell. Part (e)(ii) earned 2 points; 1 point for recognizing that six moles of electrons were transferred and 1 point for substituting and calculating the free energy value and reporting the answer correctly in kJ/mol_{rxn}.

Sample: 2B
Score: 8

This response earned 8 points. Part (c) earned 1 of 2 points for using the calculated moles of Al from part (a) to calculate the moles of CO_2; the second point was not earned because incorrect values for temperature and pressure were substituted into the ideal gas law equation, which resulted in an incorrect answer. Part (e)(ii) earned 1 point for recognizing that six moles of electrons were transferred but the second point was not earned because the answer was calculated correctly in J/mol but reported in kJ/mol.

Question 2 (continued)

Sample: 2C
Score: 6

This response earned 6 points. One point was in part (c) for using the calculated moles of Al from part (a) to calculate the moles of CO_2. The second point was not earned because the wrong value for the temperature (574 instead of 301) was substituted in the ideal gas law equation. In part (d) the point was not earned because the issue of ion mobility was not cited. In part (e)(i) 1 point was earned for calculating voltage of the cell. Neither point was earned in part (e)(ii). The number of moles of electrons transferred is incorrect and the calculation of $\Delta G°$, though consistent with the incorrect number of moles of electrons, was not actually converted to kJ/mol_{rxn} despite the unit given with the numerical value.