Question 3

Hydrogen gas burns in air according to the equation below.

$$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(l)$$

(a) Calculate the standard enthalpy change, ΔH°_{298}, for the reaction represented by the equation above. (The molar enthalpy of formation, ΔH°_f, for $H_2O(l)$ is -285.8 kJ mol^{-1} at 298 K.)

$\Delta H^\circ_{298} = [2\,(-285.8)] - [2(0) + 1(0)] = -571.6$ kJ mol^{-1}	1 point is earned for the correct answer.

(b) Calculate the amount of heat, in kJ, that is released when 10.0 g of $H_2(g)$ is burned in air.

$q = 10\text{ g H}_2 \times \dfrac{1\text{ mol H}_2}{2.016\text{ g H}_2} \times \dfrac{285.8\text{ kJ}}{1\text{ mol H}_2} = 1.42 \times 10^3\text{ kJ}$	1 point is earned for the correct setup. 1 point is earned for the correct answer.

(c) Given that the molar enthalpy of vaporization, ΔH°_{vap}, for $H_2O(l)$ is 44.0 kJ mol^{-1} at 298 K, what is the standard enthalpy change, ΔH°_{298}, for the reaction $2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$?

$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(l)$ $\quad -571.6$ kJ $2\ H_2O(l) \rightarrow 2\ H_2O(g)$ $\quad +2(44.0)$ kJ ——————————————— $2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$ $\quad -483.6$ kJ	1 point is earned for the correct answer.

A fuel cell is an electrochemical cell that converts the chemical energy stored in a fuel into electrical energy. A cell that uses H_2 as the fuel can be constructed based on the following half-reactions.

Half-reaction	E° (298 K)
$2\ H_2O(l) + O_2(g) + 4\ e^- \rightarrow 4\ OH^-(aq)$	0.40 V
$2\ H_2O(l) + 2\ e^- \rightarrow H_2(g) + 2\ OH^-(aq)$	-0.83 V

Question 3 (continued)

(d) Write the equation for the overall cell reaction.

$2\ H_2O(l)\ +\ O_2(g)\ +\ 4\ e^- \rightarrow 4\ OH^-(aq)$ $2\ H_2(g)\ +\ 4\ OH^-(aq) \rightarrow 4\ H_2O(l)\ +\ 4\ e^-$ ——————————— $2\ H_2(g)\ +\ O_2(g) \rightarrow 2\ H_2O(l)$	1 point is earned for the correct equation.

(e) Calculate the standard potential for the cell at 298 K.

$E° = 0.40\ \text{V} - (-0.83\ \text{V}) = 1.23\ \text{V}$	1 point is earned for the correct answer.

(f) Assume that 0.93 mol of $H_2(g)$ is consumed as the cell operates for 600. seconds.

(i) Calculate the number of moles of electrons that pass through the cell.

$0.93\ \text{mol}\ H_2 \times \frac{2\ \text{mol}\ e^-}{1\ \text{mol}\ H_2} = 1.9\ \text{mol}\ e^-$	1 point is earned for the correct answer.

(ii) Calculate the average current, in amperes, that passes through the cell.

$1.9\ \text{mol}\ e^- \times \frac{96{,}500\ \text{C}}{1\ \text{mol}\ e^-} = 1.8 \times 10^5\ \text{C}$ $I = \frac{q}{t} = \frac{1.8 \times 10^5\ \text{C}}{600.\ \text{s}} = 3.0 \times 10^2\ \text{amps}$	1 point is earned for calculation of the charge in coulombs. 1 point is earned for calculation of the current in amperes.

(g) Some fuel cells use butane gas, C_4H_{10}, rather than hydrogen gas. The overall reaction that occurs in a butane fuel cell is $2\ C_4H_{10}(g) + 13\ O_2(g) \rightarrow 8\ CO_2(g) + 10\ H_2O(l)$. What is one environmental advantage of using fuel cells that are based on hydrogen rather than on hydrocarbons such as butane?

Hydrogen fuel cells produce only water as a product, unlike fuel cells that use hydrocarbons, which release carbon dioxide. Carbon dioxide contributes to global warming via the enhanced atmospheric greenhouse effect.	1 point is earned for an acceptable environmental advantage.

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(c) Given that the molar enthalpy of vaporization, ΔH°_{vap}, for $H_2O(l)$ is 44.0 kJ mol^{-1} at 298 K, what is the standard enthalpy change, ΔH°_{298}, for the reaction $2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$?

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$2\ H_2O(l) + 2\ e^- \rightarrow H_2(g) + 2\ OH^-(aq)$	−0.83 V

(d) Write the equation for the overall cell reaction.

(e) Calculate the standard potential for the cell at 298 K.

(f) Assume that 0.93 mol of $H_2(g)$ is consumed as the cell operates for 600. seconds.

(i) Calculate the number of moles of electrons that pass through the cell.

(ii) Calculate the average current, in amperes, that passes through the cell.

(g) Some fuel cells use butane gas, C_4H_{10}, rather than hydrogen gas. The overall reaction that occurs in a butane fuel cell is $2\ C_4H_{10}(g) + 13\ O_2(g) \rightarrow 8\ CO_2(g) + 10\ H_2O(l)$. What is one environmental advantage of using fuel cells that are based on hydrogen rather than on hydrocarbons such as butane?

3a) $\Delta H = \Delta H$ products − ΔH reactants

$= 2(-285.8\text{ kJ/mol}) - 0$

$= -571.6$ kJ/mol

3b) 10g H_2 = 5 moles H_2 $\quad \frac{5\text{ moles}}{2\text{ moles}} \cdot 571.6\text{ kJ} = $ 1429 kJ

3c) $-571.6 + 2(44) = -483.6$ kJ/mol

$\Delta H + (\Delta H_{vap})2 = -483.6$ kJ/mol

3d) $2H_2O_{(l)} + O_{2(g)} + 4e^- \rightarrow 4OH^-_{(aq)}$

$2(2OH^-_{(aq)} + H_{2(g)} \rightarrow 2e^- + 2H_2O_{(l)})$

$O_{2(g)} + 4e^- + 2H_{2(g)} \rightarrow 4e^- + 2H_2O$

$O_{2(g)} + 2H_{2(g)} \rightarrow 2H_2O_{(l)}$

3e) Ered Cathode − Ered Anode = E°

$.40 - (-.83) = 1.23$ V

3Fi) $\frac{.93 \text{ mol } H_2}{} \Big| \frac{2 \text{ mole } e^-}{1 \text{ mole } H_2} = 1.86$ mol e^-

3Fii) 1.86 mol e^- · 96500 coulomb/mol e^- = 179490 coulombs

$I = \frac{q}{t}$ $\frac{179490}{600} = 299.15$ amps <u>299 amps</u>

3g) Fuel cells that contain H_2 only have H_2O as a product where butane gas cells also produce CO_2 which harms our earth by trapping in heat.

ADDITIONAL PAGE FOR ANSWERING QUESTION 3

3a) $\Delta H^\circ_{298} = (2)(-285.8) - (0+0) =$ **−571.6 kJ/mol rxn**

3b) $10.0g\ H_2 \cdot \frac{1 mol}{2.016g\ H_2} = 4.96 mol\ H_2$

$4.96 mol\ H_2 \cdot \frac{-571.6 kJ}{2 mol\ H_2} = -1418 kJ$ change = **1418 kJ released**

3c) $\Delta H_{vap}^\circ = 2 mol\ H_2O \cdot \frac{44 kJ}{mol\ H_2O} =$ **88 kJ/mol rxn**

3d) $2H_2O(l) + O_2(g) + 4e^- \rightarrow 4OH^-(aq)$ $E^\circ = 0.40V$

$2H_2(g) + 4OH^-(aq) \rightarrow 4H_2O(l) + 4e^-$ $E^\circ = 0.83V$

$2H_2O(l) + O_2(g) + 2H_2(g) \rightarrow 4H_2O(l)$

3e) $E^\circ_{cell} = E_{rxn1} + E_{rxn2} = 0.40V + 0.83V =$ **1.23V**

3f) $0.93 mol\ H_2 \cdot \frac{4 mol\ e^-}{2 mol\ H_2} =$ **1.86 mol e⁻**

$I = \frac{q}{t} \rightarrow q: 1.86 mol\ e^- \cdot \frac{96,500 coulombs}{mol\ e^-} = 179490$ Coulombs

$I = \frac{q}{t} = \frac{179490C}{600sec} =$ **299.15 Coulombs/second**

3g.) Burning hydrocarbons produces carbon dioxide gas, which a greenhouse gas. Greenhouse gases trap heat in the atmosphere and therefore may be viewed as a waste product of burning butane. Fuel cells based on hydrogen will not produce CO_2 alongside the water.

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ADDITIONAL PAGE FOR ANSWERING QUESTION 3

3.a) $\Delta H° = \Sigma \Delta H_f$ prod $- \Sigma \Delta H_f$ React

$\Delta H° = 2(-285.8\ KJ/mol) - [2(0)+0] =$ **$-571.6\ KJ/mol$**

b) $\left(\frac{10.0g\ H_2}{1}\right)\left(\frac{1\ mol\ H_2}{2.016g\ H_2}\right)\left(\frac{2mol\ H_2O}{2mol\ H_2}\right)\left(\frac{-571.6KJ}{1mol\ H_2O}\right) =$ **$-2840KJ$**

c) $\Delta H = \Sigma \Delta H$ prod $- \Sigma \Delta H$ react

$\Delta H = 2(44.0\ KJ/mol) - [2(0)+0] =$ **$88.0\ KJ/mol$**

d) ~~$2H_2O +$~~ $O_2 +$ ~~$4e^-$~~ $\rightarrow$ ~~$4OH^-$~~ .4v

$2(H_2 + 2OH^- \rightarrow 2H_2O + 2e^-)$ .83v

$2H_2 +$ ~~$4OH^-$~~ $\rightarrow$ ~~4~~ $2H_2O +$ ~~$4e^-$~~

$2H_2 + O_2 \rightarrow 2H_2O$

e) $\mathcal{E}_{cation} - \mathcal{E}_{anion} = \mathcal{E}_{cell} = .83 - .40 =$ **.43v**

f) i. $(.93mol\ H_2)\left(\frac{2mol\ e^-}{1mol\ H_2}\right) =$ **$1.9mol\ e^-$**

ii. $(1.9mol\ e^-)\left(\frac{96\ 500\ coul}{1mol\ e^-}\right)\left(\frac{1}{600\ sec}\right) = \frac{305.58\bar{3}\ coul}{sec} \approx$ **310A**

g) Fuels cells based on hydrogen only produce water (2mol H_2O for every 2mol H_2 & 1mol O_2). Whereas, hydrocarbons require large amounts of oxygen & produced large amounts of CO_2.

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Question 3

Overview

This question assessed students' understanding of selected concepts of thermochemistry, electrochemistry, and environmental chemistry. Thermochemistry concepts included the determination of a standard enthalpy change, applications of Hess's law, and stoichiometric determination of heats of reaction given mole or mass amounts. Electrochemistry concepts included the determination of cell reactions from half-cell reactions, the determination of standard cell potentials from half-cell potentials, and applications of Faraday's law. Finally, students were asked about the potential impact of carbon dioxide emissions on global climate.

Sample: 3A
Score: 10

This response earned all 10 available points. Part (a) earned 1 point for calculating the correct enthalpy change with units for the given chemical equation. Part (b) earned 2 points for the correct calculation of heat released for the combustion of 10.0 g of hydrogen. Part (c) earned 1 point for the correct calculation of the enthalpy of combustion of two moles of hydrogen to produce two moles of water vapor. Part (d) earned 1 point for the correct cell reaction. Part (e) earned 1 point for the correct standard cell potential. Part (f)(i) earned 1 point for the correct number of moles of electrons that pass through the cell when 0.93 mole of hydrogen gas is consumed. Part (f)(ii) earned 2 points: 1 point earned for the correct calculation of charge in coulombs, and 1 point for the correct calculation of current in amperes. Part (g) earned 1 point for indicating the environmental advantage of H_2 fuel cells not producing CO_2 and contributing to global warming.

Sample: 3B
Score: 8

Part (c) earned no point for the incorrect calculation of the enthalpy of vaporization of two moles of water. Part (d) earned no point for the unreduced cell reaction indicating two nonparticipating moles of water.

Sample: 3C
Score: 6

Part (b) earned 1 point for an indication of the conversion of 10.0 g of H_2 to moles, but no point was earned for the incorrect calculation of heat released. Part (c) earned no point for the calculation of the standard enthalpy of vaporization of 2 moles of water. Part (e) earned no point for incorrectly calculating the standard cell potential. Part (g) did not earn the point because no connection is made to a specific environmental advantage.