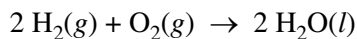


**AP<sup>®</sup> CHEMISTRY**  
**2011 SCORING GUIDELINES**

**Question 3**

Hydrogen gas burns in air according to the equation below.



- (a) Calculate the standard enthalpy change,  $\Delta H_{298}^\circ$ , for the reaction represented by the equation above.  
(The molar enthalpy of formation,  $\Delta H_f^\circ$ , for  $\text{H}_2\text{O}(l)$  is  $-285.8 \text{ kJ mol}^{-1}$  at 298 K.)

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

- (b) Calculate the amount of heat, in kJ, that is released when 10.0 g of  $\text{H}_2(g)$  is burned in air.

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

- (c) Given that the molar enthalpy of vaporization,  $\Delta H_{vap}^\circ$ , for  $\text{H}_2\text{O}(l)$  is  $44.0 \text{ kJ mol}^{-1}$  at 298 K, what is the standard enthalpy change,  $\Delta H_{298}^\circ$ , for the reaction  $2 \text{H}_2(g) + \text{O}_2(g) \rightarrow 2 \text{H}_2\text{O}(g)$  ?

$2 \text{H}_2(g) + \text{O}_2(g) \rightarrow 2 \text{H}_2\text{O}(l) \quad -571.6 \text{ kJ}$ $2 \text{H}_2\text{O}(l) \rightarrow 2 \text{H}_2\text{O}(g) \quad +2(44.0) \text{ kJ}$ <hr style="width: 50%; margin-left: 0;"/> $2 \text{H}_2(g) + \text{O}_2(g) \rightarrow 2 \text{H}_2\text{O}(g) \quad -483.6 \text{ kJ}$	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  $\text{H}_2$  as the fuel can be constructed based on the following half-reactions.

Half-reaction	$E^\circ$ (298 K)
$2 \text{H}_2\text{O}(l) + \text{O}_2(g) + 4 e^- \rightarrow 4 \text{OH}^-(aq)$	0.40 V
$2 \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{H}_2(g) + 2 \text{OH}^-(aq)$	-0.83 V

**AP<sup>®</sup> CHEMISTRY**  
**2011 SCORING GUIDELINES**

**Question 3 (continued)**

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

$2 \text{H}_2\text{O}(l) + \text{O}_2(g) + 4 e^- \rightarrow 4 \text{OH}^-(aq)$ $2 \text{H}_2(g) + 4 \text{OH}^-(aq) \rightarrow 4 \text{H}_2\text{O}(l) + 4 e^-$ <hr style="width: 50%; margin: 10px auto;"/> $2 \text{H}_2(g) + \text{O}_2(g) \rightarrow 2 \text{H}_2\text{O}(l)$	1 point is earned for the correct equation.
--	---

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

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

(f) Assume that 0.93 mol of  $\text{H}_2(g)$  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.
---	---

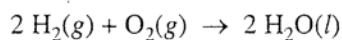
(ii) Calculate the average current, in amperes, that passes through the cell.

$1.9 \text{ mol } e^- \times \frac{96,500 \text{ C}}{1 \text{ mol } e^-} = 1.8 \times 10^5 \text{ C}$ $I = \frac{q}{t} = \frac{1.8 \times 10^5 \text{ C}}{600. \text{ s}} = 3.0 \times 10^2 \text{ amps}$	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,  $\text{C}_4\text{H}_{10}$ , rather than hydrogen gas. The overall reaction that occurs in a butane fuel cell is  $2 \text{C}_4\text{H}_{10}(g) + 13 \text{O}_2(g) \rightarrow 8 \text{CO}_2(g) + 10 \text{H}_2\text{O}(l)$ . 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.
--	--

3. Hydrogen gas burns in air according to the equation below.



- (a) Calculate the standard enthalpy change,  $\Delta H_{298}^\circ$ , for the reaction represented by the equation above.  
(The molar enthalpy of formation,  $\Delta H_f^\circ$ , for  $\text{H}_2\text{O}(\text{l})$  is  $-285.8 \text{ kJ mol}^{-1}$  at 298 K.)
- (b) Calculate the amount of heat, in kJ, that is released when 10.0 g of  $\text{H}_2(\text{g})$  is burned in air.
- (c) Given that the molar enthalpy of vaporization,  $\Delta H_{\text{vap}}^\circ$ , for  $\text{H}_2\text{O}(\text{l})$  is  $44.0 \text{ kJ mol}^{-1}$  at 298 K, what is the standard enthalpy change,  $\Delta H_{298}^\circ$ , for the reaction  $2 \text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2 \text{H}_2\text{O}(\text{g})$ ?

A fuel cell is an electrochemical cell that converts the chemical energy stored in a fuel into electrical energy. A cell that uses  $\text{H}_2$  as the fuel can be constructed based on the following half-reactions.

Half-reaction	$E^\circ$ (298 K)
$2 \text{H}_2\text{O}(\text{l}) + \text{O}_2(\text{g}) + 4 e^- \rightarrow 4 \text{OH}^-(\text{aq})$	0.40 V
$2 \text{H}_2\text{O}(\text{l}) + 2 e^- \rightarrow \text{H}_2(\text{g}) + 2 \text{OH}^-(\text{aq})$	-0.83 V

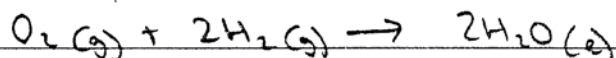
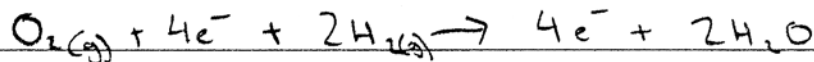
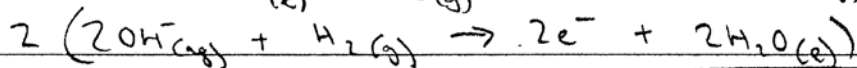
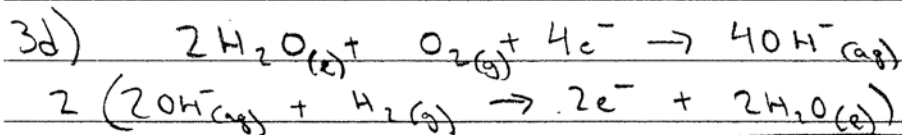
- (d) Write the equation for the overall cell reaction.
- (e) Calculate the standard potential for the cell at 298 K.
- (f) Assume that 0.93 mol of  $\text{H}_2(\text{g})$  is consumed as the cell operates for 600. seconds.
- Calculate the number of moles of electrons that pass through the cell.
  - Calculate the average current, in amperes, that passes through the cell.
- (g) Some fuel cells use butane gas,  $\text{C}_4\text{H}_{10}$ , rather than hydrogen gas. The overall reaction that occurs in a butane fuel cell is  $2 \text{C}_4\text{H}_{10}(\text{g}) + 13 \text{O}_2(\text{g}) \rightarrow 8 \text{CO}_2(\text{g}) + 10 \text{H}_2\text{O}(\text{l})$ . What is one environmental advantage of using fuel cells that are based on hydrogen rather than on hydrocarbons such as butane?

$$\begin{aligned} 3a) \quad \Delta H &= \Delta H_{\text{products}} - \Delta H_{\text{reactants}} \\ &= 2(-285.8 \text{ kJ/mol}) - 0 \\ &= -571.6 \text{ kJ/mol} \end{aligned}$$

$$3b) \quad 10 \text{g H}_2 = 5 \text{ moles H}_2 \quad \frac{5 \text{ moles}}{2 \text{ moles}} \cdot 571.6 \text{ kJ} = \underline{1429 \text{ kJ}}$$

$$3c) \quad -571.6 + 2(44) = -483.6 \text{ kJ/mol}$$

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



$$3e) \quad E_{\text{red Cathode}} - E_{\text{red Anode}} = E^\circ$$

$$.40 - (-.83) = 1.23 \text{ V}$$

$$3Fi) \quad \frac{.93 \text{ mol H}_2}{1 \text{ mole H}_2} \times \frac{2 \text{ mole } e^-}{1 \text{ mole H}_2} = 1.86 \text{ mol } e^-$$

$$3Fii) \quad 1.86 \text{ mol } e^- \cdot 96500 \text{ coulomb/mol } e^- = 179490 \text{ coulombs}$$

$$I = \frac{q}{t} = \frac{179490}{600} = 299.15 \text{ amps} \quad \underline{299 \text{ amps}}$$

3g) Fuel cells that contain H<sub>2</sub> only have H<sub>2</sub>O as a product where butane gas cells also produce CO<sub>2</sub> which harms our earth by trapping in heat.

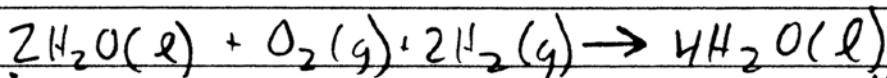
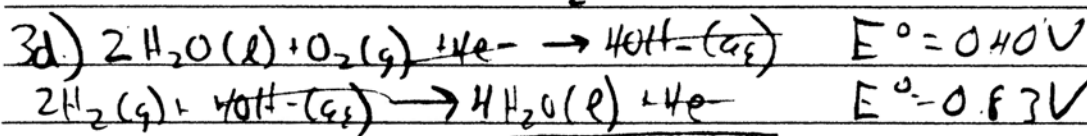
## ADDITIONAL PAGE FOR ANSWERING QUESTION 3

$$3a) \Delta H_{\text{rxn}}^{\circ} = (2)(-285.8) - (0+0) = \boxed{-571.6 \text{ kJ/mol rxn}}$$

$$3b) 10.0 \text{ g H}_2 \cdot \frac{1 \text{ mol}}{2.016 \text{ g H}_2} = 4.96 \text{ mol H}_2$$

$$4.96 \text{ mol H}_2 \cdot \frac{-571.6 \text{ kJ}}{2 \text{ mol H}_2} = -1418 \text{ kJ change} = \boxed{1418 \text{ kJ released}}$$

$$3c) \Delta H_{\text{vap}}^{\circ} = 2 \text{ mol H}_2\text{O} \cdot \frac{44 \text{ kJ}}{\text{mol H}_2\text{O}} = \boxed{88 \text{ kJ/mol rxn}}$$



$$3e) E_{\text{cell}}^{\circ} = E_{\text{cath}}^{\circ} + E_{\text{anod}}^{\circ} = 0.40 \text{ V} + 0.83 \text{ V} = \boxed{1.23 \text{ V}}$$

$$3f) 0.93 \text{ mol H}_2 \cdot \frac{4 \text{ mole e}^-}{2 \text{ mol H}_2} = \boxed{1.86 \text{ mole e}^-}$$

$$t = \frac{q}{F} \rightarrow q = 1.86 \text{ mole e}^- \cdot \frac{96,500 \text{ coulombs}}{\text{mole e}^-} = 179490 \text{ Coulombs}$$

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

3g.) Burning hydrocarbons produces carbon dioxide gas, which is 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  $\text{CO}_2$  alongside the water.

## ADDITIONAL PAGE FOR ANSWERING QUESTION 3

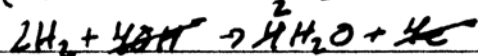
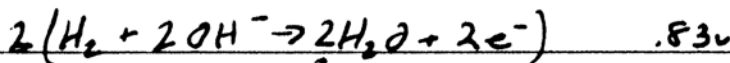
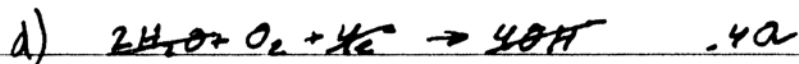
$$3.a) \Delta H^\circ = \sum \Delta H_f \text{ prod} - \sum \Delta H_f \text{ react}$$

$$\Delta H^\circ = 2(-285.8 \text{ kJ/mol}) - [2(0) + 0] = \boxed{-571.6 \text{ kJ/mol}}$$

$$b) \left( \frac{10.0 \text{ g H}_2}{1} \right) \left( \frac{1 \text{ mol H}_2}{2.016 \text{ g H}_2} \right) \left( \frac{2 \text{ mol H}_2\text{O}}{2 \text{ mol H}_2} \right) \left( \frac{-571.6 \text{ kJ}}{1 \text{ mol H}_2\text{O}} \right) = \boxed{-2840 \text{ kJ}}$$

$$c) \Delta H = \sum \Delta H \text{ prod} - \sum \Delta H \text{ react}$$

$$\Delta H = 2(44.0 \text{ kJ/mol}) - [2(0) + 0] = \boxed{88.0 \text{ kJ/mol}}$$



$$e) E_{\text{cath}} - E_{\text{anion}} = E_{\text{cell}} = .83 - .40 = \boxed{.43 \text{ V}}$$

$$f) i. (.93 \text{ mol H}_2) \left( \frac{2 \text{ mol e}^-}{1 \text{ mol H}_2} \right) = \boxed{1.9 \text{ mol e}^-}$$

$$ii. (1.9 \text{ mol e}^-) \left( \frac{96500 \text{ coul}}{1 \text{ mol e}^-} \right) \left( \frac{1}{600 \text{ sec}} \right) = \frac{305.583 \text{ coul}}{\text{sec}} \approx \boxed{310 \text{ A}}$$

g) Fuel cells based on hydrogen only produce water (2 mol H<sub>2</sub>O for every 2 mol H<sub>2</sub> & 1 mol O<sub>2</sub>). Whereas, hydrocarbons require large amounts of oxygen & produce large amounts of CO<sub>2</sub>.

**AP<sup>®</sup> CHEMISTRY**  
**2011 SCORING COMMENTARY**

**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<sub>2</sub> fuel cells not producing CO<sub>2</sub> 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<sub>2</sub> 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.