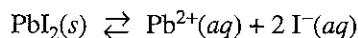


**AP[®] CHEMISTRY
2006 SCORING GUIDELINES**

Question 1

1. Answer the following questions that relate to solubility of salts of lead and barium.

- (a) A saturated solution is prepared by adding excess $\text{PbI}_2(s)$ to distilled water to form 1.0 L of solution at 25°C . The concentration of $\text{Pb}^{2+}(aq)$ in the saturated solution is found to be $1.3 \times 10^{-3} M$. The chemical equation for the dissolution of $\text{PbI}_2(s)$ in water is shown below.



- (i) Write the equilibrium-constant expression for the equation.

$K_{sp} = [\text{Pb}^{2+}][\text{I}^{-}]^2$	One point is earned for the correct expression.
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- (ii) Calculate the molar concentration of $\text{I}^{-}(aq)$ in the solution.

By stoichiometry, $[\text{I}^{-}] = 2 \times [\text{Pb}^{2+}]$, thus $[\text{I}^{-}] = 2 \times (1.3 \times 10^{-3}) = 2.6 \times 10^{-3} M$	One point is earned for the correct concentration.
--	--

- (iii) Calculate the value of the equilibrium constant, K_{sp} .

$K_{sp} = [\text{Pb}^{2+}][\text{I}^{-}]^2 = (1.3 \times 10^{-3})(2.6 \times 10^{-3})^2$ $= 8.8 \times 10^{-9}$	One point is earned for a value of K_{sp} that is consistent with the answers in parts (a)(i) and (a)(ii).
--	--

- (b) A saturated solution is prepared by adding $\text{PbI}_2(s)$ to distilled water to form 2.0 L of solution at 25°C . What are the molar concentrations of $\text{Pb}^{2+}(aq)$ and $\text{I}^{-}(aq)$ in the solution? Justify your answer.

The molar concentrations of $\text{Pb}^{2+}(aq)$ and $\text{I}^{-}(aq)$ would be the same as in the 1.0 L solution in part (a) (i.e., $1.3 \times 10^{-3} M$ and $2.6 \times 10^{-3} M$, respectively). The concentrations of solute particles in a saturated solution are a function of the constant, K_{sp} , which is independent of volume.	One point is earned for the concentrations (or stating they are the same as in the solution described in part (a)) and justification.
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**AP[®] CHEMISTRY
2006 SCORING GUIDELINES**

Question 1 (continued)

- (c) Solid NaI is added to a saturated solution of PbI_2 at 25°C . Assuming that the volume of the solution does not change, does the molar concentration of $\text{Pb}^{2+}(\text{aq})$ in the solution increase, decrease, or remain the same? Justify your answer.

<p>$[\text{Pb}^{2+}]$ will decrease.</p> <p>The $\text{NaI}(\text{s})$ will dissolve, increasing $[\text{I}^-]$; more $\text{I}^-(\text{aq})$ then combines with $\text{Pb}^{2+}(\text{aq})$ to precipitate $\text{PbI}_2(\text{s})$ so that the ion product $[\text{Pb}^{2+}][\text{I}^-]^2$ will once again attain the value of 8.8×10^{-9} (K_{sp} at 25°C).</p>	<p>One point is earned for stating that $[\text{Pb}^{2+}]$ will decrease.</p> <p>One point is earned for justification (can involve a Le Chatelier argument).</p>
--	--

- (d) The value of K_{sp} for the salt BaCrO_4 is 1.2×10^{-10} . When a 500. mL sample of $8.2 \times 10^{-6} M$ $\text{Ba}(\text{NO}_3)_2$ is added to 500. mL of $8.2 \times 10^{-6} M$ Na_2CrO_4 , no precipitate is observed.

- (i) Assuming that volumes are additive, calculate the molar concentrations of $\text{Ba}^{2+}(\text{aq})$ and $\text{CrO}_4^{2-}(\text{aq})$ in the 1.00 L of solution.

<p>New volume = 500. mL + 500. mL = 1.000 L, therefore $[\text{Ba}^{2+}]$ in 1.000 L is one-half its initial value:</p> $[\text{Ba}^{2+}] = \frac{500. \text{ mL}}{1,000. \text{ mL}} \times (8.2 \times 10^{-6} M) = 4.1 \times 10^{-6} M$ $[\text{CrO}_4^{2-}] = \frac{500. \text{ mL}}{1,000. \text{ mL}} \times (8.2 \times 10^{-6} M) = 4.1 \times 10^{-6} M$	<p>One point is earned for the correct concentration.</p>
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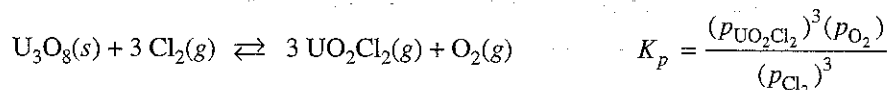
- (ii) Use the molar concentrations of $\text{Ba}^{2+}(\text{aq})$ ions and $\text{CrO}_4^{2-}(\text{aq})$ ions as determined above to show why a precipitate does not form. You must include a calculation as part of your answer.

<p>The product $Q = [\text{Ba}^{2+}][\text{CrO}_4^{2-}]$</p> $= (4.1 \times 10^{-6} M)(4.1 \times 10^{-6} M)$ $= 1.7 \times 10^{-11}$ <p>Because $Q = 1.7 \times 10^{-11} < 1.2 \times 10^{-10} = K_{sp}$, no precipitate forms.</p>	<p>One point is earned for calculating a value of Q that is consistent with the concentration values in part (d)(i).</p> <p>One point is earned for using Q to explain why no precipitate forms.</p>
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AP[®] CHEMISTRY
2007 SCORING GUIDELINES (Form B)

Question 1

A sample of solid U_3O_8 is placed in a rigid 1.500 L flask. Chlorine gas, $\text{Cl}_2(\text{g})$, is added, and the flask is heated to 862°C . The equation for the reaction that takes place and the equilibrium-constant expression for the reaction are given below.



When the system is at equilibrium, the partial pressure of $\text{Cl}_2(\text{g})$ is 1.007 atm and the partial pressure of $\text{UO}_2\text{Cl}_2(\text{g})$ is 9.734×10^{-4} atm.

(a) Calculate the partial pressure of $\text{O}_2(\text{g})$ at equilibrium at 862°C .

$\text{U}_3\text{O}_8(\text{s}) + 3 \text{Cl}_2(\text{g}) \rightleftharpoons 3 \text{UO}_2\text{Cl}_2(\text{g}) + \text{O}_2(\text{g})$ <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 10%; padding: 5px;">I</td> <td style="width: 15%; padding: 5px;">---</td> <td style="width: 15%; padding: 5px;">?</td> <td style="width: 15%; padding: 5px;">0</td> <td style="width: 15%; padding: 5px;">0</td> </tr> <tr> <td style="padding: 5px;">C</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td style="padding: 5px;">E</td> <td></td> <td style="padding: 5px;">1.007 atm</td> <td style="padding: 5px;">9.734×10^{-4} atm</td> <td style="padding: 5px;">?</td> </tr> </table> $9.734 \times 10^{-4} \text{ atm UO}_2\text{Cl}_2(\text{g}) \times \frac{(1 \text{ mol O}_2)}{(3 \text{ mol UO}_2\text{Cl}_2)} = 3.245 \times 10^{-4} \text{ atm O}_2(\text{g})$	I	---	?	0	0	C					E		1.007 atm	9.734×10^{-4} atm	?	<p style="text-align: center;">One point is earned for the correct answer.</p>
I	---	?	0	0												
C																
E		1.007 atm	9.734×10^{-4} atm	?												

(b) Calculate the value of the equilibrium constant, K_p , for the system at 862°C .

$K_p = \frac{(p_{\text{UO}_2\text{Cl}_2})^3 (p_{\text{O}_2})}{(p_{\text{Cl}_2})^3} = \frac{(9.734 \times 10^{-4})^3 (3.245 \times 10^{-4})}{(1.007)^3} = 2.931 \times 10^{-13}$	<p style="text-align: center;">One point is earned for the correct substitution.</p> <p style="text-align: center;">One point is earned for the correct answer.</p>
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(c) Calculate the Gibbs free-energy change, ΔG° , for the reaction at 862°C .

$\begin{aligned} \Delta G^\circ &= -RT \ln K_p \\ &= (-8.31 \text{ J mol}^{-1} \text{ K}^{-1})(862+273) \text{ K}(\ln (2.931 \times 10^{-13})) \\ &= 272,000 \text{ J mol}^{-1} = 272 \text{ kJ mol}^{-1} \end{aligned}$	<p style="text-align: center;">One point is earned for the correct setup.</p> <p style="text-align: center;">One point is earned for the correct answer with units.</p>
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AP[®] CHEMISTRY
2007 SCORING GUIDELINES (Form B)

Question 1 (continued)

- (d) State whether the entropy change, ΔS° , for the reaction at 862°C is positive, negative, or zero. Justify your answer.

ΔS° is <u>positive</u> because four moles of gaseous products are produced from three moles of gaseous reactants.	One point is earned for the correct explanation.
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- (e) State whether the enthalpy change, ΔH° , for the reaction at 862°C is positive, negative, or zero. Justify your answer.

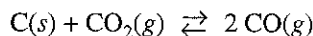
Both ΔG° and ΔS° are positive, as determined in parts (c) and (d). Thus, ΔH° must be positive because ΔH° is the sum of two positive terms in the equation $\Delta H^\circ = \Delta G^\circ + T\Delta S^\circ$.	One point is earned for the correct sign. One point is earned for a correct explanation.
--	---

- (f) After a certain period of time, 1.000 mol of $O_2(g)$ is added to the mixture in the flask. Does the mass of $U_3O_8(s)$ in the flask increase, decrease, or remain the same? Justify your answer.

The mass of $U_3O_8(s)$ will <u>increase</u> because the reaction is at equilibrium, and the addition of a product creates a "stress" on the product (right) side of the reaction. The reaction will then proceed from right to left to reestablish equilibrium so that some $O_2(g)$ is consumed (tending to relieve the stress) as more $U_3O_8(s)$ is produced.	One point is earned for a correct explanation.
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AP[®] CHEMISTRY
2008 SCORING GUIDELINES

Question 1



Solid carbon and carbon dioxide gas at 1,160 K were placed in a rigid 2.00 L container, and the reaction represented above occurred. As the reaction proceeded, the total pressure in the container was monitored. When equilibrium was reached, there was still some C(s) remaining in the container. Results are recorded in the table below.

Time (hours)	Total Pressure of Gases in Container at 1,160 K (atm)
0.0	5.00
2.0	6.26
4.0	7.09
6.0	7.75
8.0	8.37
10.0	8.37

- (a) Write the expression for the equilibrium constant, K_p , for the reaction.

$K_p = \frac{(P_{\text{CO}})^2}{P_{\text{CO}_2}}$	One point is earned for the correct expression.
---	---

- (b) Calculate the number of moles of $\text{CO}_2(g)$ initially placed in the container. (Assume that the volume of the solid carbon is negligible.)

$n = \frac{PV}{RT} = \frac{(5.00 \text{ atm})(2.00 \text{ L})}{(0.0821 \frac{\text{L atm}}{\text{mol K}})(1,160 \text{ K})} = 0.105 \text{ mol}$	One point is earned for the correct setup. One point is earned for the correct answer.
--	---

- (c) For the reaction mixture at equilibrium at 1,160 K, the partial pressure of the $\text{CO}_2(g)$ is 1.63 atm. Calculate

- (i) the partial pressure of $\text{CO}(g)$, and

$P_{\text{CO}_2} + P_{\text{CO}} = P_{\text{total}}$ $P_{\text{CO}} = P_{\text{total}} - P_{\text{CO}_2} = 8.37 \text{ atm} - 1.63 \text{ atm} = 6.74 \text{ atm}$	One point is earned for the correct answer supported by a correct method.
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AP[®] CHEMISTRY
2008 SCORING GUIDELINES

Question 1 (continued)

- (ii) the value of the equilibrium constant, K_p .

$K_p = \frac{(P_{\text{CO}})^2}{P_{\text{CO}_2}} = \frac{(6.74 \text{ atm})^2}{1.63 \text{ atm}} = 27.9$	<p>One point is earned for a correct setup that is consistent with part (a).</p> <p>One point is earned for the correct answer according to the setup.</p>
--	--

- (d) If a suitable solid catalyst were placed in the reaction vessel, would the final total pressure of the gases at equilibrium be greater than, less than, or equal to the final total pressure of the gases at equilibrium without the catalyst? Justify your answer. (Assume that the volume of the solid catalyst is negligible.)

<p>The total pressure of the gases at equilibrium with a catalyst present would be equal to the total pressure of the gases without a catalyst. Although a catalyst would cause the system to reach the same equilibrium state more quickly, it would not affect the extent of the reaction, which is determined by the value of the equilibrium constant, K_p.</p>	<p>One point is earned for the correct answer with justification.</p>
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In another experiment involving the same reaction, a rigid 2.00 L container initially contains 10.0 g of C(s), plus CO(g) and CO₂(g), each at a partial pressure of 2.00 atm at 1,160 K.

- (e) Predict whether the partial pressure of CO₂(g) will increase, decrease, or remain the same as this system approaches equilibrium. Justify your prediction with a calculation.

$Q = \frac{(P_{\text{CO}})^2}{P_{\text{CO}_2}} = \frac{(2.00 \text{ atm})^2}{2.00 \text{ atm}} = 2.00 < K_p (= 27.9),$ <p>therefore P_{CO_2} will decrease as the system approaches equilibrium.</p>	<p>One point is earned for a correct calculation involving Q or ICE calculation.</p> <p>One point is earned for a correct conclusion based on the calculation.</p>
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AP[®] CHEMISTRY
2008 SCORING GUIDELINES (Form B)

Question 1

Answer the following questions regarding the decomposition of arsenic pentafluoride, $\text{AsF}_5(g)$.

(a) A 55.8 g sample of $\text{AsF}_5(g)$ is introduced into an evacuated 10.5 L container at 105°C.

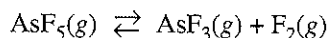
(i) What is the initial molar concentration of $\text{AsF}_5(g)$ in the container?

$\text{mol AsF}_5 = 55.8 \text{ g AsF}_5 \times \frac{1 \text{ mol AsF}_5}{169.9 \text{ g AsF}_5} = 0.328 \text{ mol}$ $[\text{AsF}_5]_i = \frac{0.328 \text{ mol AsF}_5}{10.5 \text{ L}} = 0.0313 \text{ M}$	<p>One point is earned for the correct molar mass.</p> <p>One point is earned for the correct concentration.</p>
---	--

(ii) What is the initial pressure, in atmospheres, of the $\text{AsF}_5(g)$ in the container?

$PV = nRT$ $P = \frac{0.328 \text{ mol} \times 0.0821 \text{ L atm mol}^{-1} \text{ K}^{-1} \times 378 \text{ K}}{10.5 \text{ L}} = 0.969 \text{ atm}$	<p>One point is earned for the correct substitution.</p> <p>One point is earned for the correct pressure.</p>
--	---

At 105°C, $\text{AsF}_5(g)$ decomposes into $\text{AsF}_3(g)$ and $\text{F}_2(g)$ according to the following chemical equation.



(b) In terms of molar concentrations, write the equilibrium-constant expression for the decomposition of $\text{AsF}_5(g)$.

$K = \frac{[\text{AsF}_3][\text{F}_2]}{[\text{AsF}_5]}$	<p>One point is earned for the correct equation.</p>
---	--

(c) When equilibrium is established, 27.7 percent of the original number of moles of $\text{AsF}_5(g)$ has decomposed.

(i) Calculate the molar concentration of $\text{AsF}_5(g)$ at equilibrium.

$100.0\% - 27.7\% = 72.3\%$ $[\text{AsF}_5] = 0.723 \times 0.0313 \text{ M} = 0.0226 \text{ M}$	<p>One point is earned for the correct concentration.</p>
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2008 SCORING GUIDELINES (Form B)

Question 1 (continued)

(ii) Using molar concentrations, calculate the value of the equilibrium constant, K_{eq} , at 105°C.

$[\text{AsF}_3] = [\text{F}_2] = 0.277 \times [\text{AsF}_5]$ $= 0.277 \times 0.0313 \text{ M} = 0.00867 \text{ M}$ $K_{eq} = \frac{[\text{AsF}_3][\text{F}_2]}{[\text{AsF}_5]} = \frac{[0.00867][0.00867]}{[0.0226]} = 0.00333$	<p>One point is earned for setting $[\text{AsF}_3] = [\text{F}_2]$.</p> <p><u>Note:</u> the point is not earned if the student indicates that $[\text{AsF}_3] = [\text{F}_2] = [\text{AsF}_5]$.</p> <p>One point is earned for the correct calculation of $[\text{AsF}_3]$ and $[\text{F}_2]$.</p> <p>One point is earned for the correct calculation of K_{eq}.</p>
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(d) Calculate the mole fraction of $\text{F}_2(\text{g})$ in the container at equilibrium.

$\text{mol AsF}_5 = 0.0226 \text{ M} \times 10.5 \text{ L} = 0.237 \text{ mol}$ $\text{mol F}_2 = \text{mol AsF}_3 = 0.00867 \text{ M} \times 10.5 \text{ L} = 0.0910 \text{ mol}$ $\text{mol fraction F}_2 = \frac{\text{mol F}_2}{\text{mol F}_2 + \text{mol AsF}_3 + \text{mol AsF}_5}$ $= \frac{0.0910}{0.0910 + 0.0910 + 0.237} = 0.217$ <p>OR</p> $\text{mol fraction F}_2 = \frac{0.00864}{0.00864 + 0.00864 + 0.0226} = 0.217$	<p>One point is earned for the correct calculation of the mole fraction of $\text{F}_2(\text{g})$.</p>
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AP[®] CHEMISTRY
2010 SCORING GUIDELINES

Question 1
(10 points)

Several reactions are carried out using AgBr, a cream-colored silver salt for which the value of the solubility-product-constant, K_{sp} , is 5.0×10^{-13} at 298 K.

- (a) Write the expression for the solubility-product constant, K_{sp} , of AgBr.

$K_{sp} = [\text{Ag}^+][\text{Br}^-]$	One point is earned for the correct expression (ion charges must be present; parentheses instead of square brackets not accepted).
---------------------------------------	--

- (b) Calculate the value of $[\text{Ag}^+]$ in 50.0 mL of a saturated solution of AgBr at 298 K.

Let x = equilibrium concentration of Ag^+ (and of Br^-). Then $K_{sp} = 5.0 \times 10^{-13} = x^2 \Rightarrow x = 7.1 \times 10^{-7} M$	One point is earned for the correct value with supporting work (units not necessary).
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- (c) A 50.0 mL sample of distilled water is added to the solution described in part (b), which is in a beaker with some solid AgBr at the bottom. The solution is stirred and equilibrium is reestablished. Some solid AgBr remains in the beaker. Is the value of $[\text{Ag}^+]$ greater than, less than, or equal to the value you calculated in part (b)? Justify your answer.

The value of $[\text{Ag}^+]$ after addition of distilled water is equal to the value in part (b). The concentration of ions in solution in equilibrium with a solid does <u>not</u> depend on the volume of the solution.	One point is earned for the correct answer with justification.
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- (d) Calculate the minimum volume of distilled water, in liters, necessary to completely dissolve a 5.0 g sample of AgBr(s) at 298 K. (The molar mass of AgBr is 188 g mol^{-1} .)

$5.0 \text{ g AgBr} \times \frac{1 \text{ mol AgBr}}{188 \text{ g AgBr}} = 0.0266 \text{ mol AgBr}$ $\frac{0.0266 \text{ mol}}{V} = 7.1 \times 10^{-7} \text{ mol L}^{-1} \Rightarrow V = 3.7 \times 10^4 \text{ L}$	One point is earned for the calculation of moles of dissolved AgBr. One point is earned for the correct answer for the volume of water
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**AP[®] CHEMISTRY
2010 SCORING GUIDELINES**

Question 1 (continued)

- (e) A student mixes 10.0 mL of $1.5 \times 10^{-4} M$ AgNO_3 with 2.0 mL of $5.0 \times 10^{-4} M$ NaBr and stirs the resulting mixture. What will the student observe? Justify your answer with calculations.

$[\text{Ag}^+] = \frac{(10.0 \text{ mL})(1.5 \times 10^{-4} M)}{12.0 \text{ mL}} = 1.3 \times 10^{-4} M$ $[\text{Br}^-] = \frac{(2.0 \text{ mL})(5.0 \times 10^{-4} M)}{12.0 \text{ mL}} = 8.3 \times 10^{-5} M$ $Q = [\text{Ag}^+][\text{Br}^-] = (1.3 \times 10^{-4} M)(8.3 \times 10^{-5} M) = 1.1 \times 10^{-8}$ $1.1 \times 10^{-8} > 5.0 \times 10^{-13}, \therefore \text{a precipitate will form.}$	<p>One point is earned for calculation of concentration of ions.</p> <p>One point is earned for calculation of Q and conclusion based on comparison between Q and K_{sp}.</p> <p>One point is earned for indicating the precipitation of AgBr.</p>
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- (f) The color of another salt of silver, $\text{AgI}(s)$, is yellow. A student adds a solution of NaI to a test tube containing a small amount of solid, cream-colored AgBr . After stirring the contents of the test tube, the student observes that the solid in the test tube changes color from cream to yellow.

- (i) Write the chemical equation for the reaction that occurred in the test tube.

$\text{AgBr}(s) + \text{I}^-(aq) \rightarrow \text{AgI}(s) + \text{Br}^-(aq)$ <p style="text-align: center;">OR</p> $\text{AgBr}(s) + \text{NaI}(aq) \rightarrow \text{AgI}(s) + \text{NaBr}(aq)$	<p>One point is earned for the correct equation.</p>
--	--

- (ii) Which salt has the greater value of K_{sp} : AgBr or AgI ? Justify your answer.

<p>AgBr has the greater value of K_{sp}. The precipitate will consist of the less soluble salt when both $\text{I}^-(aq)$ and $\text{Br}^-(aq)$ are present. Because the color of the precipitate in the test tube turns yellow, it must be $\text{AgI}(s)$ that precipitates; therefore K_{sp} for AgBr must be greater than K_{sp} for AgI.</p> <p style="text-align: center;">OR</p> <p>K_{eq} for the displacement reaction is $\frac{K_{sp} \text{ of AgBr}}{K_{sp} \text{ of AgI}}$. Because yellow AgI forms, $K_{eq} > 1$; therefore K_{sp} of $\text{AgBr} > K_{sp}$ of AgI.</p>	<p>One point is earned for the correct choice with justification.</p>
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AP[®] CHEMISTRY
2010 SCORING GUIDELINES (Form B)

Question 1
(10 points)

The compound butane, C_4H_{10} , occurs in two isomeric forms, *n*-butane and isobutane (2-methyl propane). Both compounds exist as gases at 25°C and 1.0 atm.

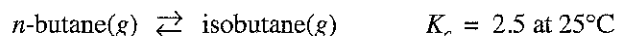
- (a) Draw the structural formula of each of the isomers (include all atoms). Clearly label each structure.

<div style="text-align: center;"> $\begin{array}{cccc} & H & H & H & H \\ & & & & \\ H & -C & -C & -C & -C & -H \\ & & & & \\ & H & H & H & H \end{array}$ <p><i>n</i>-butane</p> $\begin{array}{cccc} & H & H & H \\ & & & \\ H & -C & -C & -C & -H \\ & & & \\ & H & & H \\ & & & \\ & H-C-H & & \\ & & & \\ & H & & \end{array}$ <p>isobutane</p> </div>	<p>Two points are earned for two correct structures with correct labels.</p> <p>(Note: 1 point can be earned for either two correct structures that are mislabeled or one correct structure with or without correct label.)</p> <p style="text-align: center;">OR</p> <p>1 point can be earned for two skeletal structures (hydrogen atoms not shown) with proper labels.</p>
--	---

- (b) On the basis of molecular structure, identify the isomer that has the higher boiling point. Justify your answer.

<p>The isomer <i>n</i>-butane has the higher boiling point. London (dispersion) forces are greater among molecules of <i>n</i>-butane than they are among molecules of isobutane because molecules of <i>n</i>-butane, with its linear structure, can approach one another more closely and can form a greater number of induced temporary dipoles than molecules of isobutane, with its more compact structure, can form.</p>	<p>One point is earned for the correct choice of isomer with justification.</p>
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The two isomers exist in equilibrium as represented by the equation below.



Suppose that a 0.010 mol sample of pure *n*-butane is placed in an evacuated 1.0 L rigid container at 25°C.

- (c) Write the expression for the equilibrium constant, K_c , for the reaction.

$K_c = \frac{[\text{isobutane}]}{[n\text{-butane}]}$	<p>One point is earned for the correct equation.</p>
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AP[®] CHEMISTRY
2010 SCORING GUIDELINES (Form B)

Question 1 (continued)

- (d) Calculate the initial pressure in the container when the *n*-butane is first introduced (before the reaction starts).

$P = \frac{nRT}{V} = \frac{(0.010 \text{ mol})(0.0821 \frac{\text{L} \times \text{atm}}{\text{mol} \times \text{K}})(298 \text{ K})}{1.0 \text{ L}}$ $= 0.24 \text{ atm}$	One point is earned for the correct substitution and numerical answer.
---	--

- (e) The *n*-butane reacts until equilibrium has been established at 25°C.

- (i) Calculate the total pressure in the container at equilibrium. Justify your answer.

The total pressure in the container remains the same, 0.24 atm. As the reaction proceeds, the number of molecules in the container remains constant; one molecule of isobutane is produced for each molecule of <i>n</i> -butane consumed.	One point is earned for the correct answer with justification.
--	--

- (ii) Calculate the molar concentration of each species at equilibrium.

$K_c = \frac{[\text{isobutane}]}{[n\text{-butane}]} = \frac{x}{(0.010 - x)} = 2.5$ $x = 2.5(0.010 - x) = 0.025 - 2.5x$ $3.5x = 0.025 \Rightarrow x = 0.0071 \text{ M isobutane}$ $(0.010 \text{ M} - 0.0071 \text{ M}) = 0.003 \text{ M } n\text{-butane}$	One point is earned for the correct setup. One point is earned for both correct numerical answers.
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- (iii) If the volume of the system is reduced to half of its original volume, what will be the new concentration of *n*-butane after equilibrium has been reestablished at 25°C? Justify your answer.

Halving the volume of the container at equilibrium doubles the pressure of both isobutane and <i>n</i> -butane, which has no effect on the equilibrium because the stoichiometry of the reaction is one mole of product produced for each mole of reactant consumed. Since the number of moles of each isomer is unchanged but the volume is reduced by half, concentrations of both isomers are doubled and the concentration of <i>n</i> -butane will be $2 \times 0.003 \text{ M} = 0.006 \text{ M}$.	One point is earned for the correct answer with justification.
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Question 1 (continued)

Suppose that in another experiment a 0.010 mol sample of pure isobutane is placed in an evacuated 1.0 L rigid container and allowed to come to equilibrium at 25°C.

- (f) Calculate the molar concentration of each species after equilibrium has been established.

The concentrations of isobutane and <i>n</i> -butane would be the same as they were calculated in part (e)(ii), 0.0071 <i>M</i> and 0.003 <i>M</i> , respectively.	One point is earned for correct numerical answers or a correct statement regarding their equivalence to values obtained in part (e)(ii).
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Question 1
(10 points)

Answer the following questions about the solubility and reactions of the ionic compounds $M(OH)_2$ and MCO_3 , where M represents an unidentified metal.

(a) Identify the charge of the M ion in the ionic compounds above.

$2+$	1 point is earned for the correct charge.
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(b) At 25°C, a saturated solution of $M(OH)_2$ has a pH of 9.15.

(i) Calculate the molar concentration of $OH^-(aq)$ in the saturated solution.

$pOH = 14 - pH$ $pOH = 14 - 9.15 = 4.85$ $[OH^-] = 10^{-4.85} = 1.4 \times 10^{-5} M$	1 point is earned for the correct concentration.
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(ii) Write the solubility-product constant expression for $M(OH)_2$.

$K_{sp} = [M^{2+}] [OH^-]^2$	1 point is earned for the correct expression.
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(iii) Calculate the value of the solubility-product constant, K_{sp} , for $M(OH)_2$ at 25°C.

$[M^{2+}] = \frac{1}{2} [OH^-] = \frac{1}{2} (1.4 \times 10^{-5} M) = 7.0 \times 10^{-6} M$ $K_{sp} = [M^{2+}] [OH^-]^2 = (7.0 \times 10^{-6})(1.4 \times 10^{-5})^2$ $= 1.4 \times 10^{-15}$	1 point is earned for the correct relationship between $[M^{2+}]$ and $[OH^-]$. 1 point is earned for the correct value.
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(c) For the metal carbonate, MCO_3 , the value of the solubility-product constant, K_{sp} , is 7.4×10^{-14} at 25°C. On the basis of this information and your results in part (b), which compound, $M(OH)_2$ or MCO_3 , has the greater molar solubility in water at 25°C? Justify your answer with a calculation.

For $M(OH)_2$: $[M^{2+}]$ and molar solubility = $7.0 \times 10^{-6} M$ For MCO_3 : $K_{sp} = 7.4 \times 10^{-14} = [M^{2+}][CO_3^{2-}]$ $[M^{2+}]$ and molar solubility = $2.7 \times 10^{-7} M$ Because $7.0 \times 10^{-6} M > 2.7 \times 10^{-7} M$, $M(OH)_2$ has the greater molar solubility.	1 point is earned for the molar solubility of MCO_3 . 1 point is earned for an answer consistent with the calculated molar solubility.
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Question 1 (continued)

(d) MCO_3 decomposes at high temperatures, as shown by the reaction represented below.



A sample of MCO_3 is placed in a previously evacuated container, heated to 423 K, and allowed to come to equilibrium. Some solid MCO_3 remains in the container. The value of K_p for the reaction at 423 K is 0.0012.

(i) Write the equilibrium-constant expression for K_p of the reaction.

$K_p = P_{\text{CO}_2}$	1 point is earned for the correct expression.
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(ii) Determine the pressure, in atm, of $\text{CO}_2(g)$ in the container at equilibrium at 423 K.

$P_{\text{CO}_2} = 0.0012 \text{ atm}$	1 point is earned for the correct pressure.
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(iii) Indicate whether the value of ΔG° for the reaction at 423 K is positive, negative, or zero. Justify your answer.

$\Delta G^\circ = -RT \ln K$ $K = 0.0012 < 1$, thus $\ln K$ is negative; therefore ΔG° is positive.	1 point is earned for the correct answer with justification.
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