Question 1  
(10 points)

Answer the following questions about the solubility and reactions of the ionic compounds M(OH)₂ and MCO₃, where M represents an unidentified metal.

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

| M²⁺ | 1 point is earned for the correct charge. |

(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.

\[
pOH = 14 - pH \\
pOH = 14 - 9.15 = 4.85 \\
[OH^-] = 10^{-4.85} = 1.4 \times 10^{-5} \text{ M}
\]

1 point is earned for the correct concentration.

(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.

(iii) Calculate the value of the solubility-product constant, \(K_{sp}\), for M(OH)₂ at 25°C.

\[
[M^{2+}] = \frac{1}{2} [OH^-] = \frac{1}{2} (1.4 \times 10^{-5} \text{ M}) = 7.0 \times 10^{-6} \text{ M} \\
K_{sp} = [M^{2+}] [OH^-]^2 = (7.0 \times 10^{-6})(1.4 \times 10^{-5})^2 \\
= 1.4 \times 10^{-15}
\]

1 point is earned for the correct relationship between \([M^{2+}]\) and \([OH^-]\).

1 point is earned for the correct value.

(c) For the metal carbonate, MCO₃, the value of the solubility-product constant, \(K_{sp}\), is \(7.4 \times 10^{-14}\) at 25°C. On the basis of this information and your results in part (b), which compound, M(OH)₂ or MCO₃, 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 = \(7.0 \times 10^{-6} \text{ M}\)

For MCO₃: \(K_{sp} = 7.4 \times 10^{-14} = [M^{2+}][CO_3^{2-}]\)

\([M^{2+}]\) and molar solubility = \(2.7 \times 10^{-7} \text{ M}\)

Because \(7.0 \times 10^{-6} \text{ M} > 2.7 \times 10^{-7} \text{ M}\), M(OH)₂ has the greater molar solubility.

1 point is earned for the molar solubility of MCO₃.

1 point is earned for an answer consistent with the calculated molar solubility.
Question 1 (continued)

(d) MCO₃ decomposes at high temperatures, as shown by the reaction represented below.

\[ \text{MCO}_3(s) \rightleftharpoons \text{MO}(s) + \text{CO}_2(g) \]

A sample of MCO₃ is placed in a previously evacuated container, heated to 423 K, and allowed to come to equilibrium. Some solid MCO₃ 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.

(ii) Determine the pressure, in atm, of CO₂\(_{(g)}\) in the container at equilibrium at 423 K.

\[ P_{\text{CO}_2} = 0.0012 \text{ atm} \]

1 point is earned for the correct pressure.

(iii) Indicate whether the value of \( \Delta G^\circ \) for the reaction at 423 K is positive, negative, or zero. Justify your answer.

\[ \Delta G^\circ = -RT \ln K \]

\[ K = 0.0012 < 1, \text{ thus } \ln K \text{ is negative; therefore } \Delta G^\circ \text{ is positive.} \]

1 point is earned for the correct answer with justification.

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1.

(a) $M^{2+}$, Because $(OH)_2$ and $CO_3^{2-}$.

Answer: $2+$

(b) (i) $[OH^-] = 0.498$

$= 1.41 \times 10^{-8} M$

(ii) $M(OH)_2 \rightarrow M^{2+} + 2OH^-$

$K_{sp} = [M^{2+}][OH^-]^2$

(iii) $K_{sp} = [M^{2+}][OH^-]^2$

$= [OH^-][OH^-]^2$

$= 1.41 \times 10^{-15} M$

(c) $MCO_3 \rightarrow M^{2+} + CO_3^{2-}$

$K_{sp} = [M^{2+}][CO_3^{2-}]$

molar solubility $= [M^{2+}]$

(d) (i) $MCO_3$

$[M^{2+}] = \sqrt{K_{sp}}$

$= 2.02 \times 10^{-7} M$

(ii) $M(OH)_2$

$[M^{2+}] = \frac{K_{sp}}{Q}$

$= 7.06 \times 10^{-6} M$

$	herefore (ii) > (i)$

$\therefore M(OH)_2$ has the greater molar solubility in water at $25^\circ C$

(d) (i) $K_P = P_{CO_2}$

(ii) $K_P = P_{CO_2} = 0.0012 (at 423K)$

$	herefore P_{CO_{2,eq}} = 0.0012 atm$

(iii) $AG^\circ = -RT\ln K$

$= - (8.31 J/mol\cdot K) \times (423K) \times \ln (0.0012)$

$= +2.36 \times 10^4 J/mol \cdot K$ $\therefore positive$

GO ON TO THE NEXT PAGE.
Q1) \[ \text{OH}^- + 2. \]

b) \[
\begin{align*}
\text{pOH} &= -\log([\text{OH}^-]) \\
\Rightarrow \text{pOH} &= 10 - \text{pH} = 10 - 0.15 = 9.85 \\
\Rightarrow \text{pOH} &= -\log([\text{OH}^-]) \\
[\text{OH}^-] &= 1.0 \times 10^{-9} M
\end{align*}
\]

\[
\text{M(OH}_2\text{)}_3 \rightarrow \text{M}^{3+} + 2 \text{OH}^- \\
K_{sp} = [\text{M}^{3+}] [\text{OH}^-]^2
\]

\[
\text{III)} \\
\text{M(OH)}_n \leftrightarrow \text{M}^{2+} + 2 \text{OH}^- \\
\begin{align*}
\text{C}_n & \quad - \quad - \\
- x & \quad + x & \quad + 2x \\
\text{C}_n - x & \quad x & \quad 2x
\end{align*}
\]

\[
2x = 5 \text{OH}^- = 1.0 \times 10^{-5} \Rightarrow x = 7.0 \times 10^{-6} M
\]

\[
K_{sp} = [\text{OH}^-]^2 [\text{M}^{2+}] - (2x)^2 (x) = 2x^3 = K_{sp} = \phi (2.0 \times 10^{-6})^3
\]

\[
K_{sp} = 6.86 \times 10^{-18}
\]

C) \text{MCO}_3 \text{ has greater solubility because it has greater } K_{sp} \text{ value: } 2.4 \times 10^{-14} > 6.86 \times 10^{-18}

\[
\text{d) i)} \quad K_p = P_{\text{CO}_2} \\
\text{ii)} \quad \text{MCO}_3 \rightarrow \text{MO} + \text{CO}_2
\]

\[
K_p = x \cdot 301.2 \text{ atm}
\]

\[
\text{HE) } \Delta G \text{ is positive and the reaction is non} \\
\text{spontaneous because the value of } K_p < 1
\]

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(a) 2

(b) (i) $1.4 \times 10^{-5}$

(ii) $M^{2+}$

(iii) $1.40 \times 10^{-15}$

(c) At 25°C, 

- Solubility of $M(CO_3)_2 = 7 \times 10^{-6}$
- Solubility of $MCO_3 = 2.7 \times 10^{-7}$

$7 \times 10^{-6} < 2.7 \times 10^{-7}$

: $MCO_3$ has the greater molar solubility than compound $M(CO_3)_2$.

(d) (i) $P_{CO_2} = 0.0012$

(ii) 0.0012 atm

(iii) $K_p < 1$

Because $\Delta S \gg 0$. The value of $\Delta G^\circ$ is negative.

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Question 1

Sample: 1A
Score: 10

This response earned all 10 available points. Part (a) earned 1 point for the correct charge on the M ion. Part (b)(i) earned 1 point for the correct value for the concentration of the hydroxide ion, part (b)(ii) earned 1 point for the $K_{sp}$ expression, and part b(iii) earned 2 points: 1 point for recognizing the relationship between $[M^{2+}]$ and $[OH^-]$, where $[M^{2+}] = [OH^-]/2$, and 1 point for calculating the correct value of the $K_{sp}$. Part (c) earned 2 points: 1 point for calculating the molar solubility of MCO$_3$, and 1 point for correctly comparing the molar solubility of MCO$_3$ with the previously calculated molar solubility of M(OH)$_2$ from (b)(iii). All 3 points were earned in part (d): 1 point for the correct expression for $K_p$ in part (d)(i), 1 point in part (d)(ii) for recognizing that the value of $K_p$ was the given pressure of CO$_2$, and 1 point in part (d)(iii) for showing that the value of $\Delta G^\circ$ would be positive.

Sample: 1B
Score: 7

Part (b)(iii) earned 1 point for recognizing that there are twice as many OH$^-$ as M$^{2+}$ ions in this solution, but the second point was not earned because of the incorrect mathematics $((2x)^2(x) \neq 2x^3)$, which led to an incorrect value for the $K_{sp}$. No points were earned in part (c) as the answer just compares the $K_{sp}$ values, which is not the same as comparing the molar solubilities.

Sample: 1C
Score: 4

Although the answer to part (b)(i) is correct, it did not earn the point as no work is shown. The incorrect expression for the $K_{sp}$ did not earn the point in part (b)(ii), and the lack of any work meant that no points were earned in part (b)(iii). In part (c) the answer correctly compares the relative values for the solubilities of MCO$_3$ and M(OH)$_2$ and earned 1 point, but no work is presented to show how the values for the solubilities were obtained, so the other point was not earned. In part (d) 2 of the 3 possible points were earned: 1 point for an acceptable expression for $K_p$ in part (d)(i), and 1 point for recognizing in part (d)(ii) that the value of $K_p$ was the pressure of CO$_2$. Part (d)(iii) did not earn the point for the focus on the sign of $\Delta S$, which could not lead to the correct answer.