An 8.55 mol sample of methanol, CH$_3$OH, is placed in a 15.0 L evacuated rigid tank and heated to 327°C. At that temperature, all of the methanol is vaporized and some of the methanol decomposes to form carbon monoxide gas and hydrogen gas, as represented in the equation below.

\[
\text{CH}_3\text{OH}(g) \rightleftharpoons \text{CO}(g) + 2 \text{H}_2(g)
\]

(a) The reaction mixture contains 6.30 mol of CO(g) at equilibrium at 327°C.

(i) Calculate the number of moles of H$_2$(g) in the tank.

\[
\begin{align*}
\text{6.30 mol CO} & \times \frac{2 \text{ mol H}_2}{1 \text{ mol CO}} = 12.6 \text{ mol H}_2 \\
\text{1 point is earned for the correct number of moles.}
\end{align*}
\]

(ii) Calculate the number of grams of CH$_3$OH(g) remaining in the tank.

\[
\begin{align*}
\text{6.30 mol CO} & \times \frac{1 \text{ mol CH}_3\text{OH}}{1 \text{ mol CO}} = 6.30 \text{ mol CH}_3\text{OH reacted} \\
\text{8.55 mol CH}_3\text{OH}_{\text{initial}} - 6.30 \text{ mol CH}_3\text{OH}_{\text{reacted}} = 2.25 \text{ mol CH}_3\text{OH} \\
\text{2.25 mol} & \times \frac{32.042 \text{ g}}{1 \text{ mol}} = 72.1 \text{ g} \\
\text{1 point is earned for the correct number of grams.}
\end{align*}
\]

(iii) Calculate the mole fraction of H$_2$(g) in the tank.

\[
\frac{12.6 \text{ mol H}_2}{2.25 \text{ mol CH}_3\text{OH} + 6.30 \text{ mol CO} + 12.6 \text{ mol H}_2} = \frac{12.6}{21.15} = 0.596
\]

1 point is earned for the correct setup.

1 point is earned for the correct answer.

(iv) Calculate the total pressure, in atm, in the tank at 327°C.

\[
P = \frac{nRT}{V} = \frac{(21.15 \text{ mol})(0.0821 \frac{\text{L atm}}{\text{mol K}})(600 \text{ K})}{15.0 \text{ L}} = 69.5 \text{ atm}
\]

1 point is earned for the correct setup.

1 point is earned for the correct answer.
(b) Consider the three gases in the tank at 327°C: CH₃OH(g), CO(g), and H₂(g).

(i) How do the average kinetic energies of the molecules of the gases compare? Explain.

| The average kinetic energies are the same because all three gases are at the same temperature. | 1 point is earned for the correct answer and explanation. |

(ii) Which gas has the highest average molecular speed? Explain.

\[ KE = \frac{1}{2}mv^2, \] so at a given temperature the molecules with the lowest mass have the highest average speed. Therefore the molecules in H₂ gas have the highest average molecular speed.

| 1 point is earned for the correct answer and explanation. |

(c) The tank is cooled to 25°C, which is well below the boiling point of methanol. It is found that small amounts of H₂(g) and CO(g) have dissolved in the liquid CH₃OH. Which of the two gases would you expect to be more soluble in methanol at 25°C? Justify your answer.

The only attractive forces between molecules of H₂ and CH₃OH would be due to weak London dispersion forces (LDFs). In contrast, the LDFs are stronger between CO molecules and CH₃OH molecules because CO has more electrons than H₂. In addition CO is slightly polar; thus intermolecular dipole-dipole attractions can form between CO molecules and CH₃OH molecules. With stronger intermolecular interactions between molecules of CO and CH₃OH, CO would be expected to be more soluble in CH₃OH than H₂.

| 1 point is earned for the correct answer and justification. |
2. An 8.55 mol sample of methanol, CH₃OH, is placed in a 15.0 L evacuated rigid tank and heated to 327°C. At that temperature, all of the methanol is vaporized and some of the methanol decomposes to form carbon monoxide gas and hydrogen gas, as represented in the equation below.

\[ \text{CH}_3\text{OH}(g) \xrightleftharpoons{\text{CO(g) + 2 H}_2(}\text{g)} \]

(a) The reaction mixture contains 6.30 mol of CO(g) at equilibrium at 327°C.

(i) Calculate the number of moles of H₂(g) in the tank.

(ii) Calculate the number of grams of CH₃OH(g) remaining in the tank.

(iii) Calculate the mole fraction of H₂(g) in the tank.

(iv) Calculate the total pressure, in atm, in the tank at 327°C.

(b) Consider the three gases in the tank at 327°C: CH₃OH(g), CO(g), and H₂(g).

(i) How do the average kinetic energies of the molecules of the gases compare? Explain.

(ii) Which gas has the highest average molecular speed? Explain.

(c) The tank is cooled to 25°C, which is well below the boiling point of methanol. It is found that small amounts of H₂(g) and CO(g) have dissolved in the liquid CH₃OH. Which of the two gases would you expect to be more soluble in methanol at 25°C? Justify your answer.

\[ \text{No. of moles of H}_2 = 6.30 \times \frac{2}{1} \]

\[ = 12.6 \text{ moles} \]

\[ \text{No. of moles of CH}_3\text{OH} = 8.55 - 6.20 \]

\[ = 2.35 \text{ moles} \]

\[ \text{Mass of CH}_3\text{OH} \]

\[ = 2.25 \times (17.01 + 1.008(14) + 4.00) \]

\[ = 72.1 \text{ g} \]

\[ \text{Total moles of H}_2 = 6.30 + 12.6 + 2.25 \]

\[ = 21.15 \]

\[ \text{Mole fraction of H}_2 = \frac{12.6}{21.15} \]

\[ = 0.59 \]
(14) \( P = \frac{bRT}{V} \)
\[
= \frac{21.15 (0.0821)(321 + 273)}{15.0}
\]
\[
= 69.5 \text{ atm}/l
\]

1) (i) The average kinetic energies of the three gases are equal, as they are all at the same temperature and would hence have equal amounts of energy.

(ii) \( \text{H}_2 \) would have the highest molecular speed. As all three gases have equal kinetic energies, and kinetic energy = \( \frac{1}{2} m v^2 \) (mass)(velocity)^2, the gas with the lowest mass would have the highest speed, which is \( \text{H}_2 \).

(c) Carbon monoxide.

\( \text{H}_2 \) molecules can only have dipole-induced dipole interactions with the polar methanol molecule. \( \text{CO} \) on the other hand is a polar molecule and is able to form stronger hydrogen bonds with the methanol molecules. Hence, carbon monoxide would have higher solubility than hydrogen.
2. An 8.55 mol sample of methanol, CH₃OH, is heated to 327°C. At that temperature, all of the methanol is vaporized to form carbon monoxide gas and hydrogen gas, as represented by the following reaction:

$$\text{CH}_3\text{OH}(g) \rightleftharpoons \text{CO}(g) + 2 \text{H}_2(g)$$

(a) The reaction mixture contains 6.30 mol of CO(g) at equilibrium at 327°C.

(i) Calculate the number of moles of H₂(g) in the tank.

(ii) Calculate the number of grams of CH₃OH(g) remaining in the tank.

(iii) Calculate the mole fraction of H₂(g) in the tank.

(iv) Calculate the total pressure, in atm, in the tank at 327°C.

(b) Consider the three gases in the tank at 327°C: CH₃OH(g), CO(g), and H₂(g).

(i) How do the average kinetic energies of the molecules of the gases compare? Explain.

(ii) Which gas has the highest average molecular speed? Explain.

(c) The tank is cooled to 25°C, which is well below the boiling point of methanol. It is found that small amounts of H₂(g) and CO(g) have dissolved in the liquid CH₃OH. Which of the two gases would you expect to be more soluble in methanol at 25°C? Justify your answer.

\[
\begin{align*}
\text{(a)} \quad \text{CH}_3\text{OH}(g) & \rightleftharpoons \text{CO}(g) + 2 \text{H}_2(g) \\
& \text{6.73 mol} \\
\text{at } 327°C = 600 K \\
\hline
\text{(i)} \quad 6.30 \text{ mol CO} \times \frac{2 \text{ mol H}_2}{1 \text{ mol CO}} = 12.6 \text{ mol H}_2 \\
\text{(ii)} \quad 6.30 \text{ mol CO} \times \frac{1 \text{ mol CH}_3\text{OH}}{1 \text{ mol CO}} = 6.30 \text{ mol CH}_3\text{OH} \rightarrow \text{remaining CH}_3\text{OH} \\
\text{CH}_3\text{OH molar mass} = 32.042 \text{ g/mol} = 8.55 \text{ mol} - 6.30 \text{ mol} \\
\therefore 2.25 \text{ mol} \times 32.042 \text{ g} = 72.09 \text{ g} \\
\therefore 72.09 \text{ g CH}_3\text{OH remaining} \\
\text{(ii)} \quad \text{CH}_3\text{OH}(g) = \text{CO}(g) + 2 \text{H}_2(g) \\
2.25 \text{ mol} \quad 6.73 \text{ mol} \quad 12.6 \text{ mol} \\
\text{total mole} = 2.25 + 6.73 + 12.6 = 21.58 \\
\frac{\text{mole of H}_2}{\text{total mol}} = \frac{12.6}{21.15} = 0.5957 = 0.596 \\
\therefore 0.596
\end{align*}
\]

GO ON TO THE NEXT PAGE.
(a) \( \text{total pressure} = (P_{\text{CH}_3\text{OH}} + P_{\text{CO}} + P_{\text{H}_2}) \)

partial pressure.

\[ PV = nRT \]
\[ P = \frac{nRT}{V} = \frac{n(0.821)600}{15.0L} = 3.284n \]

3.284 \( \frac{2.25}{51.15} \) + 3.284

(b) (i) All three molecules have the same average kinetic energies because they are at the same temperature. According to the Kinetic Molecular theory, the average kinetic energy is directly proportional only to the temperature. Only it.

(ii) \( \text{H}_2 \) has the highest molecular speed. Molecular speed depends on the mass of the molecule. According to the Graham's Law, lighter the molecule faster its speed. In this question \( \text{H}_2 = 2g/mol \) \( \text{CH}_3\text{OH} = 32g/mol \) \( \text{CO} = 28g/mol \).

(c) I expect \( \text{CO}_2 \) to be more soluble in methanol at 25°C because \( \text{CO} \) is polar while \( \text{H}_2 \) is nonpolar. Since methanol, \( \text{CH}_3\text{OH} \) is polar it is more likely to dissolve another polar substance.
2. An 8.55 mol sample of methanol, CH₃OH, is placed in a 15
At that temperature, all of the methanol is vaporized and son
monoxide gas and hydrogen gas, as represented in the equat

\[ \text{CH}_3\text{OH}(g) \rightleftharpoons \text{CO}(g) + 2 \text{H}_2(g) \]

(a) The reaction mixture contains 6.30 mol of CO(g) at equilibrium at 327°C.

(i) Calculate the number of moles of H₂(g) in the tank.

(ii) Calculate the number of grams of CH₃OH(g) remaining in the tank.

(iii) Calculate the mole fraction of H₂(g) in the tank.

(iv) Calculate the total pressure, in atm, in the tank at 327°C.

(b) Consider the three gases in the tank at 327°C: CH₃OH(g), CO(g), and H₂(g).

(i) How do the average kinetic energies of the molecules of the gases compare? Explain.

(ii) Which gas has the highest average molecular speed? Explain.

(c) The tank is cooled to 25°C, which is well below the boiling point of methanol. It is found that small amounts of H₂(g) and CO(g) have dissolved in the liquid CH₃OH. Which of the two gases would you expect to be more soluble in methanol at 25°C? Justify your answer.

2. \[ \text{CH}_3\text{OH} \rightleftharpoons \text{CO} + 2 \text{H}_2 \]

(b) 6.30 mol of CO at 327°C.

(i) The ratio of produced CO and H₂ is 1 to 2.

Thus, if there are 6.30 mol of CO at equilibrium, there
must be, \( 2 \times 6.30 \) mol of H₂. \( \therefore 12.60 \) mol

(ii) All the carbon in the product comes from CH₃OH.

This means if there are 6.30 mol of CO, 6.30 mol of

CH₃OH were consumed,

\[
\begin{array}{l}
\text{Initial:} \quad 8.55 \text{mol} \\
\text{Change:} \quad -6.30 \text{mol} +6.30 \text{mol} +12.60 \text{mol} \\
\text{Equilibrium:} \quad 2.25 \text{mol} +6.30 \text{mol} +12.60 \text{mol} \\
\end{array}
\]

mass of CH₃OH per mole \( \times (4+1+2+16) \) g/mol = 32.8 g/mol

\( \therefore 32.8 \text{g/mol} \times 2.25 \text{mol} = 72 \text{g} \)

(iii) mole fraction of H₂ = \( \frac{\text{number of moles of H}_2}{\text{total number of moles}} \)

GO ON TO THE NEXT PAGE.
\[ \frac{12.60 \text{ mol}}{(2.25 + 12.60 + 6.30) \text{ mol}} = 0.596 \]

(iv) **Total number of moles \( n \):** 21.15 mol

- **Volume:** 15.0 L
- **\( R \):** 0.082 \( \text{ L} \cdot \text{atm} \cdot \text{K}^{-1} \cdot \text{mol}^{-1} \)
- **\( T \):** \( (273 + 327) \text{ K} = 600 \text{ K} \)

\[ PV = nRT \]

\[ P = \frac{21.15 \text{ mol} \times 0.082 \text{ atm} \cdot \text{K} \cdot \text{mol}^{-1} \cdot \text{K}^{-1} \times 600 \text{ K}}{15 \text{ L}} = 69.572 \text{ atm} \]

\[ \therefore 69.572 \text{ atm} \]

(b) (i) **All three gases are at the same temperature, 327°C.**

In this case, by comparing the **mass** of these three gases, we can also compare the kinetic energies of the molecules.

- The heavier the molecule, the smaller its kinetic energy.
- The lighter the molecules, the greater its kinetic energy.

- **\( \text{CH}_3\text{OH} \):** 17.29
- **\( \text{CO} \):** 6.30 \( \text{ mol} \) \times 28.0 \( \text{g/mol} \) = 176.49
- **\( \text{H}_2 \):** 12.60 \( \text{ mol} \) \times 2.01 \( \text{g/mol} \) = 25.29

\[ \therefore \text{H}_2 > \text{CH}_3\text{OH} > \text{CO} \]

(ii) **Comparison:**

- **\( \text{CH}_3\text{OH} \):** 17.29
- **\( \text{CO} \):** 176.49
- **\( \text{H}_2 \):** 25.29

\[ \frac{17.29}{176.49} : \frac{25.29}{1} : \frac{1.89}{2.646} : \frac{1}{1} \rightarrow \text{the ratio of average molecular speed} \]

\[ \geq \text{the larger the number, the slower it is} \]

\[ \therefore \text{H}_2 \]

(c) **Polar molecules dissolve well in polar solutions.**

Since \( \text{CH}_3\text{OH} \), methanol, is a polar solution, the **poor one of the two gases** will be more soluble in methanol.

\[ \therefore \text{C}=\text{O}^+ \text{ vs } \text{H}-\text{H} \]

\[ \therefore \text{CO} \]
Question 2

Sample: 2A  
Score: 9

This response earned all 9 possible points. Part (a) earned 6 points: 1 point in part (a)(i) for determining the correct number of moles of H₂(g), 1 point in part (a)(ii) for correctly determining the grams of CH₃OH(g) remaining in the tank, 2 points in part (a)(iii) for the correct mole fraction, and 2 points in part (a)(iv) for correctly using all the moles of gas in the tank in the Ideal Gas Law to calculate the final pressure. Part (b) earned 3 points: 1 point in part (b)(i) for appropriately connecting the average kinetic energy of the particles to the temperature, 1 point in part (b)(ii) for discussing of the inverse relationship between a particle’s mass and its speed, and 1 point in part (b)(iii) for discussing the types of intermolecular interactions that could occur between the solvent (CH₃OH) and each of the solutes (CO and H₂).

Sample: 2B  
Score: 7

Part (a)(iv) earned 1 point for correctly calculating the pressure using the Ideal Gas Law (where n represents the moles of gas in the tank) but did not earn the point because of the incorrect calculation of the final pressure. Part (b)(iii) did not earn the point as the response merely paraphrases the adage that like dissolves like; although sometimes an appropriate rule-of-thumb, this is neither a justification nor an explanation.

Sample: 2C  
Score: 5

Part (a)(iv) earned the setup point, but by expressing the answer with five significant digits the response did not earn the point. Part (b)(i) did not earn the point because the response incorrectly connects the mass of a gaseous particle to its kinetic energy. Part (b)(ii) did not earn the point, even though the answer is correct (H₂), because the explanation suggests that the ordering of the speed of gaseous molecules is inversely proportional to the amount of that material in the sample. Part (b)(iii) did not earn the point because the paraphrase of like dissolves like is not an acceptable justification.