Question 2

$$CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g)$$

2. The combustion of carbon monoxide is represented by the equation above.

(a) Determine the value of the standard enthalpy change, ΔH°_{rxn}, for the combustion of $CO(g)$ at 298 K using the following information.

$$C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g) \qquad \Delta H^\circ_{298} = -110.5 \text{ kJ mol}^{-1}$$

$$C(s) + O_2(g) \rightarrow CO_2(g) \qquad \Delta H^\circ_{298} = -393.5 \text{ kJ mol}^{-1}$$

Reverse the first equation and add it to the second equation to obtain the third equation. $CO(g) \rightarrow \frac{1}{2}O_2(g) + C(s) \quad \Delta H^\circ_{298} = +110.5 \text{ kJ mol}^{-1}$ $+\ C(s) + O_2(g) \rightarrow CO_2(g) \quad \Delta H^\circ_{298} = -393.5 \text{ kJ mol}^{-1}$ $CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g) \quad \Delta H^\circ_{rxn} = 110.5 + (-393.5)$ $= -283.0 \text{ kJ mol}^{-1}$	One point is earned for reversing the first equation. One point is earned for the correct answer (with sign).
	OR
OR $\Delta H^\circ_{rxn} = \Delta H^\circ_f$ of $CO_2(g) - \Delta H^\circ_f$ of $CO(g)$ $= -393.5 \text{ kJ mol}^{-1} - (-110.5 \text{ kJ mol}^{-1}) = -283.0 \text{ kJ mol}^{-1}$	Two points are earned for determining ΔH°_{rxn} from the enthalpies of formation. (If sign is incorrect, only one point is earned.)

(b) Determine the value of the standard entropy change, ΔS°_{rxn}, for the combustion of $CO(g)$ at 298 K using the information in the following table.

Substance	S°_{298} ($J\ mol^{-1}\ K^{-1}$)
$CO(g)$	197.7
$CO_2(g)$	213.7
$O_2(g)$	205.1

Question 2 (continued)

$\Delta S^\circ_{rxn} = 213.7 \text{ J mol}^{-1}\text{ K}^{-1} - (197.7 \text{ J mol}^{-1}\text{ K}^{-1} + \frac{1}{2}(205.1 \text{ J mol}^{-1}\text{ K}^{-1}))$ $= -86.5 \text{ J mol}^{-1}\text{ K}^{-1}$	One point is earned for taking one-half of S°_{298} for $O_2(g)$. One point is earned for the answer (with sign).

(c) Determine the standard free energy change, ΔG°_{rxn}, for the reaction at 298 K. Include units with your answer.

$\Delta G^\circ_{rxn} = \Delta H^\circ_{rxn} - T\,\Delta S^\circ_{rxn}$ $= -283.0 \text{ kJ mol}^{-1} - (298 \text{ K})(-0.0865 \text{ kJ mol}^{-1}\text{ K}^{-1})$ $\Delta G^\circ_{rxn} = -257.2 \text{ kJ mol}^{-1}$	One point is earned for substituting the values from parts (a) and (b) into the equation. One point is earned for the answer (with sign and units).

(d) Is the reaction spontaneous under standard conditions at 298 K ? Justify your answer.

Yes, the reaction is spontaneous because the value of ΔG°_{rxn} for the reaction is negative (-257.2 kJ mol^{-1}).	One point is earned for an answer with justification (consistent with the answer in part (c)).

(e) Calculate the value of the equilibrium constant, K_{eq}, for the reaction at 298 K.

$\Delta G^\circ_{rxn} = -RT\ln K_{eq} \Rightarrow \frac{\Delta G^\circ_{rxn}}{-RT} = \ln K_{eq}$ $\frac{-257{,}200 \text{ J mol}^{-1}}{-(8.31 \text{ J mol}^{-1}\text{ K}^{-1})(298 \text{ K})} = \ln K_{eq} \Rightarrow K_{eq} = 1.28 \times 10^{45}$	One point is earned for correct substitution into the equation. One point is earned for the answer.

Answer EITHER Question 2 below OR Question 3 printed on page 16. Only one of these two questions will be graded. If you start both questions, be sure to cross out the question you do not want graded. The Section II score weighting for the question you choose is 20 percent. 2A, 1

$$CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g)$$

2. The combustion of carbon monoxide is represented by the equation above.

   (a) Determine the value of the standard enthalpy change, ΔH°_{rxn}, for the combustion of $CO(g)$ at 298 K using the following information.

   $C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g)$ $\quad\quad \Delta H^\circ_{298} = -110.5\ \text{kJ mol}^{-1}$

   $C(s) + O_2(g) \rightarrow CO_2(g)$ $\quad\quad \Delta H^\circ_{298} = -393.5\ \text{kJ mol}^{-1}$

   (b) Determine the value of the standard entropy change, ΔS°_{rxn}, for the combustion of $CO(g)$ at 298 K using the information in the following table.

Substance	S°_{298} (J mol^{-1} K^{-1})
$CO(g)$	197.7
$CO_2(g)$	213.7
$O_2(g)$	205.1

   (c) Determine the standard free energy change, ΔG°_{rxn}, for the reaction at 298 K. Include units with your answer.

   (d) Is the reaction spontaneous under standard conditions at 298 K ? Justify your answer.

   (e) Calculate the value of the equilibrium constant, K_{eq}, for the reaction at 298 K.

2. a. $CO(g) \rightarrow \cancel{C(s)} + \cancel{\frac{1}{2}O_2(g)}$ $\quad \Delta H^\circ_{298} = 110.5\ \frac{kJ}{mol}$

$+ \quad \cancel{C(s)} + O_2(g) \rightarrow CO_2(g)$ $\quad \Delta H^\circ_{298} = -393.5\ \frac{kJ}{mol}$

$\cancel{CO(g) + O_2(g) \rightarrow \frac{1}{2}O_2(g) + CO_2(g) \quad \Delta H^\circ_{298} = -283.0\ \frac{kJ}{mol}}$

$\cancel{-\frac{1}{2}O_2} \quad\quad \cancel{-\frac{1}{2}O_2}$

$CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g)$ $\quad \Delta H^\circ_{rxn} = -283.0\ \frac{kJ}{mol}$

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2A2

b. $\Delta S^\circ_{rxn} = \left(213.7 \frac{J}{mol\text{-}K}\right) - \left[\left(197.7 \frac{J}{mol\text{-}K}\right) + \frac{1}{2}\left(205.1 \frac{J}{mol\text{-}K}\right)\right]$

$= 213.7 - (197.7 + 102.55)$

$= 213.7 \frac{J}{mol\text{-}K} - 300.25 \frac{J}{mol\text{-}K}$

$= -86.6 \frac{J}{mol\text{-}K}$

c. $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$

$= -283.0 \frac{kJ}{mol} - 298\cancel{K}\left(\frac{-86.6\cancel{J}}{mol\text{-}\cancel{K}}\right)\left(\frac{1kJ}{1000\cancel{J}}\right)$

$= -283.0 \frac{kJ}{mol} - -25.8 \frac{kJ}{mol}$

$= -257.2 \frac{kJ}{mol}$

d. yes the reaction is spontaneous at 298 K.
$\Delta G^\circ = -257.2 \frac{kJ}{mol}$; a negative number meaning the reaction is spontaneous.

e. $\Delta G = \Delta G^\circ + RT\ln Q$

$\Delta G = 0$ at equilibrium

$0 = \Delta G^\circ + RT\ln K$

$\Delta G^\circ = -RT\ln K$

$-257.2 \frac{kJ}{mol} = -\left(8.31 \frac{J}{mol\text{-}K}\right)\left(\frac{1kJ}{1000J}\right)(298\ K)\ln K$

$-257.2 \frac{kJ}{mol} = -2.47638 \frac{kJ}{mol} \ln K$

$\ln K = 103.8612814$

$e \qquad e$

$K_{eq} = 1.28 \times 10^{45}$

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Answer EITHER Question 2 below OR Question 3 printed on page 16. Only one of these two questions will be graded. If you start both questions, be sure to cross out the question you do not want graded. The Section II score weighting for the question you choose is 20 percent. 2B, 1

$$CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g)$$

2. The combustion of carbon monoxide is represented by the equation above.

(a) Determine the value of the standard enthalpy change, ΔH°_{rxn}, for the combustion of $CO(g)$ at 298 K using the following information. $\Delta H^\circ_{rxn} = -283.0$ kJ/mol

$$C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g) \qquad \Delta H^\circ_{298} = -110.5 \text{ kJ mol}^{-1}$$

$$C(s) + O_2(g) \rightarrow CO_2(g) \qquad \Delta H^\circ_{298} = -393.5 \text{ kJ mol}^{-1}$$

(b) Determine the value of the standard entropy change, ΔS°_{rxn}, for the combustion of $CO(g)$ at 298 K using the information in the following table. $\Delta S^\circ_{rxn} = -86.6$ J/mol K.

Substance	S°_{298} (J mol^{-1} K^{-1})
$CO(g)$	197.7
$CO_2(g)$	213.7
$O_2(g)$	205.1

(c) Determine the standard free energy change, ΔG°_{rxn}, for the reaction at 298 K. Include units with your answer. $\Delta G^\circ_{rxn} = -308.8 \frac{kJ}{mol}$

(d) Is the reaction spontaneous under standard conditions at 298 K ? Justify your answer.
no because ΔG must be positive value for the reaction to be spontaneous

(e) Calculate the value of the equilibrium constant, K_{eq}, for the reaction at 298 K.
$K_{eq} = 1.43 \times 10^{54}$

2) a) $CO(g) \rightarrow \frac{1}{2}\cancel{O_2(g)} + \cancel{C(s)}$ $\Delta H = +110.5$ kJ/mol
$\cancel{C(s)} + \cancel{O_2(g)} \rightarrow CO_2(g)$ $\Delta H = -393.5$ kJ/mol
$CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g)$ $\Delta H = 110.5 + (-393.5) = -283.0$ kJ/mol

b) $\Delta S = \Sigma \Delta S_{prod.} - \Sigma \Delta S_{react}$
$\Delta S = (213.7) - (\frac{1}{2}(205.1) + (197.7))$
$\Delta S = -86.6$ J/mol K $\qquad -86.6 J \times \frac{kJ}{1000 J} =$

c) $\Delta G = \Delta H - T\Delta S$
$\Delta G = (-283.0 \frac{kJ}{mol}) - (298K)(-.0866 \text{ kJ/mol K})$
$\Delta G^\circ_{rxn} = -308.8$ kJ/mol

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2B2

d) The reaction is not spontaneous because. ΔG must be a positive value for the reaction to be spontaneous. The ΔG for this reaction is a negative value and therefor the reaction is nonspontaneous. ΔG calculated is the amount of energy you need to make the reation occur

e) $\Delta G = -RT \ln Keq$.

$-308.8 \frac{KJ}{mol} = -(.00831)(298)(\ln Keq)$.

$\ln Keq = 124.698$.

$Keq = 1.43 \times 10^{54}$

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Answer EITHER Question 2 below OR Question 3 printed on page 16. Only one of these two questions will be graded. If you start both questions, be sure to cross out the question you do not want graded. The Section II score weighting for the question you choose is 20 percent. 2C1

$C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g) +$

$$CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g)$$

2. The combustion of carbon monoxide is represented by the equation above.

(a) Determine the value of the standard enthalpy change, ΔH°_{rxn}, for the combustion of $CO(g)$ at 298 K using the following information. ΔH prod − ΔH react

$$C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g) \qquad \Delta H^\circ_{298} = -110.5 \text{ kJ mol}^{-1}$$

$$C(s) + O_2(g) \rightarrow CO_2(g) \qquad \Delta H^\circ_{298} = -393.5 \text{ kJ mol}^{-1} \quad -393.5 \text{kJmol}$$

(b) Determine the value of the standard entropy change, ΔS°_{rxn}, for the combustion of $CO(g)$ at 298 K using the information in the following table.

Substance	S°_{298} (J mol^{-1} K^{-1})
$CO(g)$	197.7
$CO_2(g)$	213.7
$O_2(g)$	205.1

(c) Determine the standard free energy change, ΔG°_{rxn}, for the reaction at 298 K. Include units with your answer.

(d) Is the reaction spontaneous under standard conditions at 298 K ? Justify your answer.

(e) Calculate the value of the equilibrium constant, K_{eq}, for the reaction at 298 K.

2a) $\Delta H^\circ = \Sigma\Delta H f^\circ_{prod} - \Sigma\Delta H f^\circ_{react}$ $\quad \Delta H f^\circ \frac{1}{2}O_2(g) = 0$

$\Delta H^\circ_{rxn} = \Delta H f^\circ CO_2(g) - \Delta H f^\circ CO(g) = -393.5\text{kJ mol}^{-1} - -110.5\text{kJ mol}^{-1}$

$= -283 \text{ kJ mol}^{-1}$

b) $\Delta S^\circ_{rxn} = \Sigma S^\circ \text{products} - \Sigma S^\circ \text{reactants}$

$= 213.7 \text{ J mol}^{-1}\text{K}^{-1} - (197.7 + 205.1)$

$= -189.1 \text{ J mol}^{-1}\text{K}^{-1}$

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2C2

$\frac{kJ}{mol} - \left(K \cdot \frac{kJ}{mol\,K}\right.$

c) $\Delta G^\circ_{rxn} = \Delta H^\circ - T\Delta S^\circ$

$= -283\ kJ\,mol^{-1} - (298K \cdot -189.1\ J\,mol^{-1}K^{-1})$

$= -283\ kJ\,mol^{-1} - (298K \cdot -.189\ kJ\,mol^{-1}K^{-1})$

$= -226.6482\ kJ\,mol^{-1}$

~~d) Yes this reaction is spontaneous because the change in free energy is negative, and it is exothermic, ΔH°_{rxn} is negative, so excess energy is given off~~

d) Yes This reaction is spontaneous because ΔH°_{rxn} is neg. so it is a exothermic and ΔG is negative (change in free energy), and because ΔS is negative (change in entropy.)

Question 2

Overview

The intent of this question was to test students' knowledge of basic thermodynamic relationships, including enthalpy, entropy, and free energy changes, and the equilibrium constant associated with a chemical reaction. The first task was to calculate the values for enthalpy, entropy, and free energy changes from the information provided. Students were asked what the calculated thermodynamic quantities implied for the spontaneity of the reaction given, $CO + \frac{1}{2} O_2 \rightarrow CO_2$, and had to calculate the thermodynamic equilibrium constant.

Sample: 2A
Score: 9

This response earned all 9 points: 2 points for part (a), 2 points for part (b), 2 points for part (c), 1 point for part (d), and 2 points for part (e). Note that the student has an unusual way of writing the numeral "8," which is consistently used throughout the response.

Sample: 2B
Score: 7

Only 1 point was earned in part (c) because the negative sign in (−.0866 kJ/mol K) is not carried through correctly, constituting a math error. The point was not earned in part (d) because of the incorrect conclusion that a negative Gibbs free energy is an indication of nonspontaneity.

Sample: 2C
Score: 5

Only 1 point was earned in part (b) because the entropy of oxygen is not multiplied by ½, its coefficient in the combustion equation. This incorrect value is used correctly in part (c), but only 1 out of 2 points were earned in this part because the number of significant figures in the answer is off by more than one. In part (d) 1 point was earned, but part (e) is not attempted.