Thermochemistry & Thermodynamics

PSI AP Chemistry

Name ______________________

1) How many joules are equivalent to 37.7 cal?
   A) 9.01 J
   B) 4.184 J
   C) 1.51 J
   D) 158 J

2) The quantity of heat that is needed to raise the temperature of a sample of a substance 1.00 degree is called its
   A) heat capacity
   B) specific heat
   C) enthalpy
   D) kinetic energy

3) Equal masses of two substances, A & B, each absorb 25 Joules of energy. If the temperature of A increases by 4 degrees and the temperature of B increases by 8 degrees, one can say that
   A) the specific heat of A is double that of B.
   B) the specific heat of B is double that of A.
   C) the specific heat of B is negative.
   D) the specific heat of B is triple that of A.

4) If 25 J are required to change the temperature of 5.0 g of substance A by 2.0°C, what is the specific heat of substance A?
   A) 250 J/g°C
   B) 63 J/g°C
   C) 10. J/g°C
   D) 2.5 J/g°C

5) How much energy is required to change the temperature of 2.00 g aluminum from 20.0°C to 25.0°C? The specific heat of aluminum is 0.902 J/g°C.
   A) 2.3 J
   B) 9.0 J
   C) 0.36 J
   D) 0.090 J

6) Consider the thermal energy transfer during a chemical process. When heat is transferred to the system, the process is said to be ________ and the sign of ΔH is ________.
   A) exothermic, positive
   B) endothermic, negative
   C) exothermic, negative
   D) endothermic, positive
7) What is the $\Delta E$ for a system which has the following two steps:
   Step 1: The system absorbs 60 J of heat while 40 J of work are performed on it.
   Step 2: The system releases 30 J of heat while doing 70 J of work.
   A) 100 J  C) 30 J
   B) 90 J  D) zero

8) When two solutions react the container “feels hot.” Thus,
   A) the reaction is endothermic.
   B) the reaction is exothermic.
   C) the energy of the universe is increased.
   D) the energy of both the system and the surroundings is decreased.

9) The equation for the standard enthalpy of formation of $\text{N}_2\text{O}_3$ is
   A) $\text{N}_2\text{O}(g) + \text{O}_2(g) \rightarrow \text{N}_2\text{O}_3(g)$
   B) $\text{N}_2\text{O}_5(g) \rightarrow \text{N}_2\text{O}_3(g) + \text{O}_2(g)$
   C) $\text{NO}(g) + \text{NO}_2(g) \rightarrow \text{N}_2\text{O}_3(g)$
   D) $\text{N}_2(g) + \frac{3}{2} \text{O}_2(g) \rightarrow \text{N}_2\text{O}_3(g)$

10) For the general reaction, $2A + B_2 \rightarrow 2AB$, $\Delta H$ is +50.0 kJ. We can conclude that:
    A) the reaction is endothermic.
    B) the surroundings absorb energy.
    C) the standard enthalpy of formation of AB is -50.0 kJ.
    D) the molecule AB contains less energy than A or $B_2$.

11) Calculate the amount of heat needed to change 25.0 g ice at 0°C to water at 0°C.
    The heat of fusion of $\text{H}_2\text{O} = 333 \text{ J/g}$;
    A) 56.5 kJ
    B) 8.33 kJ
    C) 7.06 kJ
    D) 463 kJ

Heating Curve Practice Problems

12) What amount of heat will change 82 g of solid ice at -6 C to vapor at 120 C?
    A) 266 kJ  B) 2900 kJ  c) 300kJ  D) 235kJ

13) What amount of heat will change 75 g of liquid water at -40 C to vapor at 30 C?
    A) 500kJ  B) 40.4kJ  C) 34.5kJ  D) 31.0kJ

14) What amount of heat will change 50 g of liquid water at 25 C to gas at 350 C?
    A) 136 kJ  B) 152kJ  C) 34kJ  D) 386kJ
15) How much heat will it take to change 20 g of liquid water at 15°C to vapor or steam at 220°C?
A) 115kJ  B) 110kJ  C) 57kJ  D) 567 kJ

16) What amount of heat will change 30 g of liquid water at 50°C to 250°C?
A) 8280J  B) 67800J  C) 6270J  D) 82350J

17) What amount of heat will change 30 g of ice at -40°C to liquid water at 70°C?
A) 21.1kJ  B) 8.7kJ  C) 2.5kJ  D) 12.4kJ

Hess's law

18. Calculate the enthalpy of combustion of C₃H₆:

\[ \text{C}_3\text{H}_6(g) + \frac{9}{2}\text{O}_2(g) \rightarrow 3\text{CO}_2 + 3\text{H}_2\text{O} \]

using the following data:

\[ 3\text{C(s)} + 3\text{H}_2(g) \rightarrow \text{C}_3\text{H}_6(g) \quad \Delta H^\circ = 53.3 \text{ kJ} \]
\[ \text{C(s)} + \text{O}_2(g) \rightarrow \text{CO}_2(g) \quad \Delta H^\circ = -394 \text{ kJ} \]
\[ \text{H}_2(g) + \frac{1}{2}\text{O}_2(g) \rightarrow \text{H}_2\text{O}(l) \quad \Delta H^\circ = -286 \text{ kJ} \]

A) -1517 kJ  B) 1304 kJ  C) -626 kJ  D) -2093 kJ

19. Which one of the following would have an enthalpy of formation value (\(\Delta H_f\)) of zero?
A) \(\text{H}_2\text{O}(g)\)  B) \(\text{O}(g)\)  C) \(\text{H}_2\text{O}(l)\)  D) \(\text{O}_2(g)\)

20. Calculate the heat of vaporization of titanium (IV) chloride: \(\text{TiCl}_4(l) \rightarrow \text{TiCl}_4(g)\)
using the following enthalpies of reaction:

\[ \text{Ti(s)} + 2\text{Cl}_2(g) \rightarrow \text{TiCl}_4(l) \quad \Delta H^\circ = -804.2 \text{ kJ} \]
\[ \text{TiCl}_4(g) \rightarrow 2\text{Cl}_2(g) + \text{Ti(s)} \quad \Delta H^\circ = 763.2 \text{ kJ} \]

A) -1567 kJ  B) -783.7 kJ  C) 1165 kJ  D) 41 kJ

21. Calculate the enthalpy of reaction for: \(\text{D} + \text{F} \rightarrow \text{G} + \text{M}\)
Use the following equations and data:

\[ \text{G} + \text{C} \rightarrow \text{A} + \text{B} \quad \Delta H^\circ = +277 \text{ kJ} \]
\[ \text{C} + \text{F} \rightarrow \text{A} \quad \Delta H^\circ = +303 \text{ kJ} \]
\[ \text{D} \rightarrow \text{B} + \text{M} \quad \Delta H^\circ = -158 \text{ kJ} \]

A) -132 kJ  B) -422 kJ  C) +422 kJ  D) +132 kJ
22. \( \text{Ge(s)} + \frac{1}{2} \text{O}_2(g) \rightarrow \text{GeO(s)} \quad \Delta H^\circ = -255 \text{ kJ} \)
\( \text{Ge(s)} + \text{O}_2(g) \rightarrow \text{GeO}_2(s) \quad \Delta H^\circ = -534.7 \text{ kJ} \)
Can be manipulated to give \( \Delta H^\circ \) for the following
\( \text{GeO(s)} + \frac{1}{2} \text{O}_2(g) \rightarrow \text{GeO}_2(s) \). Calculate the enthalpy value.
A) 279.9kJ  B) -279.9  C) 789.7  D) -789.7

23) Show how the equations
\( \frac{1}{2} \text{N}_2 + \text{O}_2(g) \rightarrow \text{NO}_2(g) \Delta H^\circ = +33.8 \text{kJ} \)
\( \frac{1}{2} \text{N}_2 (g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{NO}(g) \Delta H^\circ = + 90.37 \) can be manipulated to calculate the enthalpy for the below reaction.
\( \text{NO}(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{NO}_2 \Delta H^\circ = ? \)
A) 56.57kJ  B) 124.17  C) -56.57kJ  D) -124.17 kJ

24) Show how the equations
\( \text{N}_2\text{O}_4(g) \rightarrow 2\text{NO}_2(g) \Delta H^\circ = +57.93 \text{ kJ} \)
\( 2\text{NO}(g) + \text{O}_2(g) \rightarrow 2\text{NO}_2(g) \Delta H^\circ = -113.14 \text{ kJ} \) Can be manipulated to give \( \Delta H^\circ \) for the following
\( 2\text{NO}(g) + \text{O}_2(g) \rightarrow \text{N}_2\text{O}_4(g) \)
A) 55.21 kJ  B) -223.41 kJ  C) 171.07kJ  D) -171.07kJ

25) We can generate hydrogen chloride by hating a mixture of sulfuric acid and potassium chloride according to the equation:
\( 2\text{KCl(s)} + \text{H}_2\text{SO}_4(l) \rightarrow 2\text{HCl(g)} + \text{K}_2\text{SO}_4(s) \) Calculate \( \Delta H^\circ \) in kj for this reaction from the following thermochemical equations:
\( \text{HCl(g)} + \text{KOH(s)} \rightarrow \text{KCl(s)} + \text{H}_2\text{O(l)} \quad \Delta H^\circ = -203.6 \text{ kJ} \)
\( \text{H}_2\text{SO}_4(l) + 2\text{KOH(s)} \rightarrow \text{K}_2\text{SO}_4(s) + 2\text{H}_2\text{O(l)} \quad \Delta H^\circ = -342.4 \text{ kJ} \)
A) 64.8kJ  B) -138.8kJ  C) 138.8 kJ  D) -64.8kJ

26) Calculate \( \Delta H^\circ \) in kJ for the following reaction, the preparation of the unstable acid nitrous acid, \( \text{HNO}_2 \). \( \text{HCl(g)} + \text{NaNO}_2(s) \rightarrow \text{HNO}_2(l) + \text{NaCl(s)} \)
Use the following equations:
\( 2\text{NaCl(s)} + \text{H}_2\text{O(l)} \rightarrow 2 \text{HCl(g)} + \text{Na}_2\text{O(s)} \Delta H^\circ = +507.31 \text{ kJ} \)
\( \text{NO(g)} + \text{NO}_2(g) + \text{Na}_2\text{O(s)} \rightarrow 2\text{NaNO}_2(s) \Delta H^\circ = -427.14 \text{ kJ} \)
\( \text{NO(g)} + \text{NO}_2(g) \rightarrow \text{N}_2\text{O}_2(g) + \text{O}_2(g) \) \( \Delta H^\circ = -42.68 \text{kJ} \)
\[
2 \text{HNO}_2(\text{l}) \rightarrow \text{N}_2\text{O}(\text{g}) + \text{O}_2(\text{g}) + \text{H}_2\text{O}(\text{l}) \quad \Delta H^\circ = +34.35 \text{kJ}
\]

A) -156.93 kJ  B) 156.93 kJ  C) 78.47 kJ  D) -78.47 kJ

27) Barium oxide reacts with sulfuric acid as follows
\[
\text{BaO(s) + H}_2\text{SO}_4(\text{l}) \rightarrow \text{BaSO}_4(\text{s}) + \text{H}_2\text{O(l)}
\]
Calculate \( \Delta H^\circ \) in kJ for the above reaction using the equations below.

\[
\text{SO}_3(\text{g}) + \text{H}_2\text{O(l)} \rightarrow \text{H}_2\text{SO}_4(\text{l}) \quad \Delta H^\circ = -78.2 \text{kJ}
\]
\[
\text{BaO (s) + SO}_3(\text{g}) \rightarrow \text{BaSO}_4(\text{s}) \quad \Delta H^\circ = -213 \text{kJ}
\]

A) 291.2 kJ  B) -134.8 kJ  C) 67.4 kJ  D) 269.6 kJ

**Enthalpy calculations**

Thermodynamic Quantities for Selected Substances at 298.15 K (25°C)

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \Delta H^\circ (\text{kJ/mol}) )</th>
<th>( \Delta G^\circ (\text{kJ/mol}) )</th>
<th>( S^\circ (\text{J/K/mol}) )</th>
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<tbody>
<tr>
<td>Carbon</td>
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<tr>
<td>C (s, diamond)</td>
<td>1.88</td>
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<td>C (s, graphite)</td>
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<td>H(_2)O (l)</td>
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<th>Substance</th>
<th>( \Delta H^\circ (\text{kJ/mol}) )</th>
<th>( \Delta G^\circ (\text{kJ/mol}) )</th>
<th>( S^\circ (\text{J/K/mol}) )</th>
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<td>Calcium</td>
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<td>CaCl(_2) (s)</td>
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<td>-748.1</td>
<td>104.6</td>
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</table>
28) The value of $\Delta H^\circ$ for the oxidation of solid elemental sulfur to gaseous sulfur trioxide,

$$2S(s, \text{rhombic}) + 3O_2(g) \rightarrow 2SO_3(g)$$

is __________ kJ/mol.
A) +790.4
B) -790.4
C) +395.2
D) -395.2
E) +105.1

29) The value of $\Delta H^\circ$ for the decomposition of gaseous sulfur trioxide to its component elements,

$$2SO_3(g) \rightarrow 2S(s, \text{rhombic}) + 3O_2(g)$$

is __________ kJ/mol.
A) +790.4
B) -790.4
C) +395.2
D) -395.2
E) +105.1

30) The value of $\Delta H^\circ$ for the oxidation of solid elemental sulfur to gaseous sulfur dioxide,

$$S(s, \text{rhombic}) + O_2(g) \rightarrow SO_2(g)$$

is __________ kJ/mol.
31) The value of $\Delta H^\circ$ for the formation of POCl$_3$ from its constituent elements, $P_2(g) + O_2(g) + 3Cl_2(g) \rightarrow 2$POCl$_3$(g) is $\boxed{-1228.7}$ kJ/mol.

32) Calculate the standard enthalpy of the reaction for the process $3$NO(g) $\rightarrow$ N$_2$O(g) + NO$_2$(g) using the standard enthalpies of formation (in kJ/mol):

\[ \text{NO} = 90; \ N_2O = 82.1; \ NO_2 = 34.0 \]

\[ A) \ -153.9 \text{ kJ} \]
\[ B) \ 206 \text{ kJ} \]
\[ C) \ -26.1 \text{ kJ} \]
\[ D) \ 386 \text{ kJ} \]

33). The standard molar enthalpy of combustion is -1277.3 kJ for the combustion of ethanol.

\[ \text{C}_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(g) \]

Calculate the standard molar enthalpy of formation for ethanol based on the following standard enthalpies of formation:

\[ \Delta H^\circ_f \text{ CO}_2 = -393.5 \text{ kJ/mol} \]
\[ \Delta H^\circ_f \text{ H}_2\text{O} = -241.8 \text{ kJ/mol} \]

\[ A) \ -642.7 \text{ kJ/mol} \]
\[ B) \ -235.1 \text{kJ/mol} \]
\[ C) \ 235.1 \text{kJ/mol} \]
\[ D) \ 642.7 \text{kJ/mol} \]

**Entropy**

34). Which of the following represents an increase in entropy?

A) freezing of water
B) boiling of water
C) crystallization of salt from a supersaturated solution
D) the reaction $2$NO(g) $\rightarrow$ N$_2$O$_2$(g)
E) the reaction $2$H$_2$(g) + O$_2$(g) $\rightarrow$ 2H$_2$O(g)
35). The enthalpy of vaporization of methanol (CH$_3$OH) is 35.3 kJ/mol at the boiling point of 64.2°C. Calculate the entropy change for methanol going from a liquid to vapor.

A) 600. J/K•mol
B) 551 J/K•mol
C) 105 J/K•mol
D) -105 J/K•mol
E) -551 J/K•mol

36). Calculate the standard entropy change for the following reaction, Cu(s) + $\frac{1}{2}$ O$_2$(g) $\rightarrow$ CuO(s), given that

$S^\circ$: [Cu(s)] = 33.15 J/K•mol
$S^\circ$: [O$_2$(g)] = 205.14 J/K•mol
$S^\circ$: [CuO(s)] = 42.63 J/K•mol

A) 195.66 J/K
B) 93.09 J/K
C) -45.28 J/K
D) -93.09 J/K
E) 195.66 J/K

37). In which of the following reactions do you expect to have a decrease in entropy?

A) Fe(s) $\rightarrow$ Fe(l)
B) Fe(s) + S(s) $\rightarrow$ FeS(s)
C) 2 Fe(s) + 3/2 O$_2$(g) $\rightarrow$ Fe$_2$O$_3$(s)
D) HF(l) $\rightarrow$ HF(g)
E) 2 H$_2$O$_2$(l) $\rightarrow$ 2 H$_2$O(l) + O$_2$(g)

38). The normal boiling point of water is 100.0 °C and its molar enthalpy of vaporization is 40.67 kJ/mol. What is the change in entropy in the system in J/K when 39.3 grams of steam at 1 atm condenses to a liquid at the normal boiling point?

A) 88.8
B) -88.8
C) -238
D) 373
E) -40.7

39). The normal boiling point of C$_2$Cl$_3$F$_3$ is 47.6°C and its molar enthalpy of vaporization is 27.49 kJ/mol. What is the change in entropy in the system in J/K when 28.6 grams of C$_2$Cl$_3$F$_3$ vaporizes to a gas at the normal boiling point?

A) -13.1
40) Which of the following statements is false?
A) The change in entropy in a system depends on the initial and final states of the system and the path taken from one state to the other.
B) Any irreversible process results in an overall increase in entropy.
C) The total entropy of the universe increases in any spontaneous process.
D) Entropy increases with the number of microstates of the system.

41) Which reaction produces a decrease in the entropy of the system?
A) CaCO$_3$(s) → CaO(s) + CO$_2$(g)
B) 2C(s) + O$_2$(g) → 2CO(g)
C) CO$_2$(s) → CO$_2$(g)
D) 2H$_2$(g) + O$_2$(g) → 2H$_2$O(l)
E) H$_2$O(l) → H$_2$O(g)

42) Which reaction produces an increase in the entropy of the system?
A) Ag$^+$(aq) + Cl$^-$(aq) → AgCl(s)
B) CO$_2$(s) → CO$_2$(g)
C) H$_2$(g) + Cl$_2$(g) → 2HCl(g)
D) N$_2$(g) + 3H$_2$(g) → 2NH$_3$(g)
E) H$_2$O(l) → H$_2$O(s)

43) $\Delta S^\circ$ is negative for the reaction ___________.
A) 2SO$_2$(g) + O$_2$(g) → 2SO$_3$(g)
B) NH$_4$Cl(s) → NH$_3$(g) + HCl(g)
C) PbCl$_2$(s) → Pb$^{2+}$(aq) + 2Cl$^-$(aq)
D) 2C(s) + O$_2$(g) → 2CO(g)
E) H$_2$O(l) → H$_2$O(g)

44) $\Delta S^\circ$ is positive for the reaction ___________.
A) Pb(NO$_3$)$_2$(aq) + 2KI(aq) → PbI$_2$(s) + 2KNO$_3$(aq)
B) 2H$_2$O(g) → 2H$_2$(g) + O$_2$(g)
C) H$_2$O(g) → H$_2$O(s)
D) NO(g) + O$_2$(g) → NO$_2$(g)
E) Ag$^+$(aq) + Cl$^-$(aq) → AgCl(s)

45) $\Delta S^\circ$ is negative for the reaction ___________.
A) 2H$_2$O(g) → 2H$_2$(g) + O$_2$(g)
B) Mg(NO$_3$)$_2$(aq) + 2NaOH(aq) → Mg(OH)$_2$(s) + 2NaNO$_3$(aq)
C) H$_2$O(l) → H$_2$O(g)
D) C$_6$H$_{12}$O$_6$(s) → 6C(s) + 6H$_2$(g) + 3O$_2$(g)
E) NaCl(aq) → Na$^+$(aq) + Cl$^-$(aq)
46) Of the following, the entropy of gaseous __________ is the largest at 25°C and 1 atm.
A) $H_2$
B) $C_2H_6$
C) $C_2H_2$
D) $CH_4$
E) $C_2H_4$

![Thermodynamic Quantities Table]

47) The value of $\Delta S^\circ$ for the catalytic hydrogenation of acetylene to ethene, $C_2H_2 (g) + H_2(g) \rightarrow C_2H_4(g)$, is ________ J/K·mol.
A) +18.6
B) +550.8
C) +112.0
D) -112.0
E) -18.6

48) The combustion of acetylene in the presence of excess oxygen yields carbon dioxide and water:

$$2C_2H_2 (g) + 5O_2 \rightarrow 4CO_2(g) \ 2H_2O(l)$$

The value of $\Delta S^\circ$ for this reaction is ________ J/K·mol.
49) The value of $\Delta S^\circ$ for the oxidation of carbon to carbon dioxide,
\[ \text{C(s graphite)} + \text{O}_2(g) \rightarrow \text{CO}_2(g) \]
is \[ \text{__________ J/K}\cdot\text{mol} \]. The combustion of carbon, as in charcoal briquettes, in the presence of abundant oxygen produces carbon dioxide.
A) +424.3
B) +205.0
C) -205.0
D) -2.9
E) +2.9

50) The combustion of ethane in the presence of excess oxygen yields carbon dioxide and water: \[ 2\text{C}_2\text{H}_6(g) + 7\text{O}_2(g) \rightarrow 4\text{CO}_2(g) + 6\text{H}_2\text{O}(l) \]
The value of $\Delta S^\circ$ for this reaction is \[ \text{__________ J/K}\cdot\text{mol} \].
A) +718.0
B) -620.1
C) -718.0
D) -151.0
E) +151.0

Use the table below to answer the questions that follow.

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<tr>
<th>Substance</th>
<th>$\Delta H^\circ$ (kJ/mol)</th>
<th>$\Delta G^\circ$ (kJ/mol)</th>
<th>$S^\circ$ (J/K\cdot mol)</th>
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<td></td>
</tr>
<tr>
<td>O$_2$ (g)</td>
<td>0</td>
<td>0</td>
<td>205.0</td>
</tr>
<tr>
<td>H$_2$O (l)</td>
<td>-258.83</td>
<td>-237.13</td>
<td>69.91</td>
</tr>
<tr>
<td>Phosphorous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P$_2$ (g)</td>
<td>144.3</td>
<td>103.7</td>
<td>218.1</td>
</tr>
<tr>
<td>PCl$_3$</td>
<td>-288.1</td>
<td>-269.6</td>
<td>311.7</td>
</tr>
<tr>
<td>POCl$_3$ (g)</td>
<td>-542.2</td>
<td>-502.5</td>
<td>325</td>
</tr>
<tr>
<td>Sulfur</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S (s, rhombic)</td>
<td>0</td>
<td>0</td>
<td>31.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>SO(_2) (g)</td>
<td>-269.9</td>
<td>-300.4</td>
<td>248.5</td>
</tr>
<tr>
<td>SO(_3) (g)</td>
<td>-395.2</td>
<td>-370.4</td>
<td>256.2</td>
</tr>
</tbody>
</table>

51) The value of \(\Delta S^\circ\) for the oxidation of solid elemental sulfur to gaseous sulfur trioxide,
\[
2\text{S(s,rhombic) +3O}_2\text{(g) → 2SO}_3\text{(g)}
\]
is __________ J/K·mol.
A) +19.3 
B) -19.3 
C) +493.1 
D) -166.4 
E) -493.1 

52) The value of \(\Delta S^\circ\) for the decomposition of gaseous sulfur trioxide to solid elemental sulfur and gaseous oxygen,
\[
2\text{SO}_3\text{(g) → 2S(s,rhombic) +3O}_2\text{(g)}
\]
is __________ J/K·mol.
A) +19.3 
B) -19.3 
C) +493.1 
D) +166.4 
E) -493.1 

53) The value of \(\Delta S^\circ\) for the formation of POCl\(_3\) from its constituent elements,
\[
\text{P}_2\text{(g) +O}_2\text{(g) + 3Cl}_2\text{(g) → 2POCl}_3\text{(g)}
\]
is __________ J/K·mol.
A) -442.0 
B) +771.0 
C) -321.0 
D) -771.0 
E) +321.0 

54) The value of \(\Delta S^\circ\) for the decomposition of POCl\(_3\) into its constituent elements,
\[
2\text{POCl}_3\text{(g) → P}_2\text{(g) +O}_2\text{(g) + 3Cl}_2\text{(g)}
\]
is __________ J/K·mol.
A) +771.0 
B) +442.0 
C) -321.0 
D) -771.0 
E) +321.0 

55) The value of \(\Delta S^\circ\) for the decomposition of calcium chloride into its constituent elements,
\[
\text{CaCl}_2\text{(s) → Ca(s) + Cl}_2
\]
is __________ J/K \cdot mol.
A) -104.6  
B) +104.6  
C) +369.0  
D) -159.8  
E) +159.8

**Free energy: Use the above table**

56) The value of $\Delta G^\circ$ at 25°C for the decomposition of gaseous sulfur trioxide to solid elemental sulfur and gaseous oxygen,
$$2\text{SO}_3(g) \rightarrow 2\text{S(s,rhombic)} + 3\text{O}_2(g)$$
is __________ kJ/mol.
A) +740.8  
B) -370.4  
C) +370.4  
D) -740.8  
E) +185.2

57) The value of $\Delta G^\circ$ at 25°C for the decomposition of gaseous sulfur dioxide to solid elemental sulfur and gaseous oxygen,
$$\text{SO}_2(g) \rightarrow 2\text{S(s,rhombic)} + \text{O}_2(g)$$
is __________ kJ/mol.
A) +395.2  
B) +269.9  
C) -269.9  
D) +300.4  
E) -300.4

58) The value of $\Delta G^\circ$ at 25°C for the formation of POCl$_3$ from its constituent elements,
$$\text{P}_2(g) + \text{O}_2(g) + 3\text{Cl}_2(g) \rightarrow 2\text{POCl}_3(g)$$
is __________ kJ/mol.
A) -1,108.7  
B) +1,108.7  
C) -606.2  
D) +606.2  
E) -1,005

59) The value of $\Delta G^\circ$ at 25°C for the formation of phosphorous trichloride from its constituent elements,
$$\text{P}_2(g) + 3\text{Cl}_2(g) \rightarrow 2\text{PCl}_3(g)$$
is __________ kJ/mol.
A) -539.2
B) +539.2
C) -642.9
D) +642.9
E) -373.9

60) The standard Gibbs free energy of formation of __________ is zero.
   (a) H₂O(l)   (b) Na(s)   (c) H₂(g)
A) (a) only
B) (b) only
C) (c) only
D) (b) and (c)
E) (a), (b), and (c)

61) The standard Gibbs free energy of formation of __________ is zero.
   (a) Al (s)   (b) Br₂ (l)   (c) Hg (l)
A) (a) only
B) (b) only
C) (c) only
D) (b) and (c)
E) (a), (b), and (c)

I. Gibbs free energy & temperature; Gibbs free energy & equilibrium constant

62) The value of ΔG° at 373 K for the oxidation of solid elemental sulfur to
gaseous sulfur dioxide,
   \[ \text{S(s,rhombic)} + \text{O}_2(\text{g}) \rightarrow \text{SO}_2 \]
   is __________ kJ/mol. At 298 K, ΔH° for this reaction is -269.9 kJ/mol, and
   ΔS° is +11.6 J/K.
A) -300.4
B) +300.4
C) -4,597
D) +4,597
E) -274.2

63) Given the thermodynamic data in the table below, calculate the equilibrium
constant (at 298 K) for the reaction:
   \[ 2\text{SO}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2\text{SO}_3(\text{g}) \]

<table>
<thead>
<tr>
<th>Substance</th>
<th>ΔH° (kJ/mol)</th>
<th>S° (J/mol·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>-297</td>
<td>249</td>
</tr>
<tr>
<td>O₂</td>
<td>0</td>
<td>205</td>
</tr>
<tr>
<td>SO₃</td>
<td>-395</td>
<td>256</td>
</tr>
</tbody>
</table>
A) $2.37 \times 10^{24}$
B) 1.06
C) 1.95
D) $3.82 \times 10^{23}$
E) More data are needed.
64) The equilibrium constant for a reaction is 0.48 at 25°C. What is the value of ∆G° (kJ/mol) at this temperature?
A) 1.8
B) -4.2
C) 1.5 x 10²
D) 4.2
E) More information is needed.

65) The equilibrium constant for the following reaction is 5.0 x 10⁸ at 25°C.

\[ \text{N}_2(g) + 3\text{H}_2(g) \rightarrow 2\text{NH}_3(g) \]

The value of ∆G° for this reaction is ________ kJ/mol.
A) 22
B) -4.2
C) -25
D) -50
E) -22

66) Consider the reaction:

\[ \text{NH}_3(g) + \text{HCl}(g) \rightarrow \text{NH}_4\text{Cl}(s) \]

Given the following table of thermodynamic data at 298 K:

<table>
<thead>
<tr>
<th>Substance</th>
<th>ΔH° (kJ/mol)</th>
<th>S° (J/K·mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃(g)</td>
<td>-46.19</td>
<td>192.50</td>
</tr>
<tr>
<td>HCl(g)</td>
<td>-92.30</td>
<td>186.69</td>
</tr>
<tr>
<td>NH₄Cl(s)</td>
<td>-314.40</td>
<td>94.60</td>
</tr>
</tbody>
</table>

The value of K for the reaction at 25°C is __________.
A) 150
B) 9.2 x 10¹⁵
C) 8.4 x 10⁴
D) 1.1 x 10⁻¹⁶
E) 1.4 x 10⁸

67) The entropy of the universe is ________.
A) constant
B) continually decreasing
C) continually increasing
D) zero
E) the same as the energy, E
68) Consider the reaction:

\[
\text{FeO(s) + Fe(s) + O}_2 \rightarrow \text{Fe}_2\text{O}_3
\]

Given the following table of thermodynamic data at 298 K:

<table>
<thead>
<tr>
<th>Substance</th>
<th>ΔH° (kJ/mol)</th>
<th>S° (J/K·mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeO(s)</td>
<td>-271.9</td>
<td>60.75</td>
</tr>
<tr>
<td>Fe(s)</td>
<td>0</td>
<td>27.15</td>
</tr>
<tr>
<td>O₂(g)</td>
<td>0</td>
<td>205.00</td>
</tr>
<tr>
<td>Fe₂O₃(s)</td>
<td>-822.16</td>
<td>89.96</td>
</tr>
</tbody>
</table>

The value K for the reaction at 25°C is __________.

A) 370  
B) 5.9 \times 10^4  
C) 3.8 \times 10^{-14}  
D) 7.1 \times 10^{85}  
E) 8.1 \times 10^{19}

69) For the reaction: \( \text{C(s) + H}_2\text{O(g) → CO(g) + H}_2\text{(g)} \), \( \Delta H^\circ = 131.3 \text{ kJ/mol} \) and \( \Delta S^\circ = 133.6 \text{ J/K·mol} \) at 298 K. At temperatures greater than __________°C this reaction is spontaneous under standard conditions.

A) 273  
B) 325  
C) 552  
D) 710  
E) 983

70) For the reaction: \( \text{C}_2\text{H}_6(g) \rightarrow \text{C}_2\text{H}_4(g) + \text{H}_2(g) \), \( \Delta H^\circ \) is +137 kJ/mol and \( \Delta S^\circ \) is +120 J/K·mol. This reaction is __________.

A) spontaneous at all temperatures  
B) spontaneous only at high temperature  
C) spontaneous only at low temperature  
D) nonspontaneous at all temperatures

71) For a reaction to be spontaneous under standard conditions at all temperatures, the signs of \( \Delta H^\circ \) and \( \Delta S^\circ \) must be __________ and __________, respectively.

A) +, +  
B) +, -  
C) -, +  
D) -, -  
E) +, 0
72) A reaction that is not spontaneous at low temperature can become spontaneous at high temperature if $\Delta H^\circ$ is _________ and $\Delta S^\circ$ is _________.

A) +, +  
B) -, -  
C) +, -  
D) -, +  
E) +, 0

73) Given the following table of thermodynamic data, complete the following sentence. The vaporization of $\text{PCl}_3(l)$ is __________.

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\Delta H^\circ_f$ (kJ/mol)</th>
<th>$S^\circ$ (J/K·mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{PCl}_3(g)$</td>
<td>-288.07</td>
<td>311.7</td>
</tr>
<tr>
<td>$\text{PCl}_3(l)$</td>
<td>-319.6</td>
<td>217</td>
</tr>
</tbody>
</table>

A) nonspontaneous at low temperature and spontaneous at high temperature  
B) spontaneous at low temperature and nonspontaneous at high temperature  
C) spontaneous at all temperatures  
D) nonspontaneous at all temperatures  
E) not enough information given to draw a conclusion

74) Consider the reaction:

$$\text{Ag}^+(aq) + \text{Cl}^-(aq) \rightarrow \text{AgCl(s)}$$

Given the following table of thermodynamic data, determine the temperature (in °C) above which the reaction is nonspontaneous under standard conditions.

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\Delta H^\circ_f$ (kJ/mol)</th>
<th>$S^\circ$ (J/K·mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Ag}^+(aq)$</td>
<td>105.90</td>
<td>73.93</td>
</tr>
<tr>
<td>$\text{Cl}^-(aq)$</td>
<td>-167.2</td>
<td>56.5</td>
</tr>
<tr>
<td>$\text{AgCl(s)}$</td>
<td>-127.0</td>
<td>96.11</td>
</tr>
</tbody>
</table>

A) 1230  
B) 150  
C) 432  
D) 133  
E) 1640
75) Consider the reaction:

\[ \text{NH}_3(g) + \text{HCl}(g) \rightarrow \text{NH}_4\text{Cl}(s) \]

Given the following table of thermodynamic data, determine the temperature (in °C) above which the reaction is nonspontaneous.

<table>
<thead>
<tr>
<th>Substance</th>
<th>(\Delta H^\circ_f) (kJ/mol)</th>
<th>(S^\circ) (J/K·mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{NH}_3(g))</td>
<td>-46.19</td>
<td>192.50</td>
</tr>
<tr>
<td>(\text{HCl}(g))</td>
<td>-92.30</td>
<td>186.69</td>
</tr>
<tr>
<td>(\text{NH}_4\text{Cl}(s))</td>
<td>-314.40</td>
<td>94.60</td>
</tr>
</tbody>
</table>

A) This reaction is spontaneous at all temperatures.
B) 618.1
C) 432.8
D) 345.0
E) 1235

76) Given the following table of thermodynamic data, complete the following sentence. The vaporization of \(\text{TiCl}_4\) is __________.

<table>
<thead>
<tr>
<th>Substance</th>
<th>(\Delta H^\circ_f) (kJ/mol)</th>
<th>(S^\circ) (J/K·mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{TiCl}_4) (g)</td>
<td>-763.2</td>
<td>354.9</td>
</tr>
<tr>
<td>(\text{TiCl}_4) (l)</td>
<td>-804.2</td>
<td>221.9</td>
</tr>
</tbody>
</table>

A) spontaneous at all temperatures
B) spontaneous at low temperature and nonspontaneous at high temperature
C) nonspontaneous at low temperature and spontaneous at high temperature
D) nonspontaneous at all temperatures
E) not enough information given to draw a conclusion

77) With thermodynamics, one cannot determine __________.
A) the speed of a reaction
B) the direction of a spontaneous reaction
C) the extent of a reaction
D) the value of the equilibrium constant
E) the temperature at which a reaction will be spontaneous

78) Which one of the following statements is true about the equilibrium constant for a reaction if \(\Delta G^\circ\) for the reaction is negative?
A) \(K = 0\)
B) \(K = 1\)
C) \(K > 1\)
D) \(K < 1\)
E) More information is needed.
79) Calculate ΔG˚ (in kJ/mol) for the following reaction at 1 atm and 25°C:
   C₂H₆(g) + O₂(g) → CO₂(g) + H₂O(l) [unbalanced]
   ΔGᵣ° C₂H₆(g) = -32.89 kJ/mol; ΔGᵣ° CO₂(g) = -394.4 kJ/mol;
   ΔGᵣ° H₂O(l) = -237.13 kJ/mol

80) Calculate ΔG˚ (in kJ/mol) for the following reaction at 1 atm and 25°C:
   C₂H₆(g) + O₂(g) → CO₂(g) + H₂O(l) [unbalanced]
   ΔHᵣ° C₂H₆(g) = -84.7 kJ/mol ; ΔSᵣ° C₂H₆(g) = 229.5 J/Kmol
   ΔHᵣ° CO₂(g) = -393.5 kJ/mol ; ΔSᵣ° CO₂(g) = 213.6 J/Kmol
   ΔHᵣ° H₂O(l) = -285.8 kJ/mol ; ΔSᵣ° H₂O(l) = 69.9 J/Kmol
   ΔSᵣ° O₂(g) = 205.0 J/Kmol

81) Find the temperature (in K) above which a reaction with a ΔH˚ of 123.0 kJ/mol and a ΔS˚ of 90.00 J/Kmol becomes spontaneous.

82) Find the temperature (in K) above which a reaction with a ΔH˚ of 53.0 kJ/mol and a ΔS˚ of 100.00 J/Kmol becomes spontaneous.

83) Calculate ΔG˚ for the autoionization of water at 25°C. Kᵯₜ = 1.0 × 10⁻¹⁴

   True/False

84) The entropy of a pure crystalline substance at 0°C is zero.

85) The more negative ΔG˚ is for a given reaction, the larger the value of the corresponding equilibrium constant, K.

86) The formation ½ A₂ + 2 B₂ + C → CAB₄ has an enthalpy of formation of -104 kJ and a change in entropy of -60.8 J/K at 30 °C. What is ΔG and spontaneity of the reaction?
   A) -85.6 kJ, spontaneous
   B) -18.3 kJ, not spontaneous
   C) +18.3 kJ, spontaneous
   D) +85.6 kJ, not spontaneous
   E) -85.6 kJ, not spontaneous

87) If ΔH and ΔS are both negative or positive, then ΔG has a _________ sign.
   A) positive
   B) negative
   C) variable
   D) large
   E) no
88) At what temperature would a given reaction become spontaneous if \( \Delta H = +119 \) kJ and \( \Delta S = +263 \) J/K?
A) 452 K
B) 2210 K
C) 382 K
D) 2.21 K
E) 363 K

89). The free energy change for a given reaction is -36.2 kJ. What is the equilibrium constant at 298 K?
A) 0.985
B) 2.22 x 10^6
C) 1.01
D) 8.32 x 10^-7
E) 3.25 x 10^6

90). Given the following information, calculate \( \Delta G^\circ \) for the reaction below at 25°C:
SnCl\(_4\)(l) + 2 H\(_2\)O(l) → SnO\(_2\)(s) + 4 HCl(g)
\( \Delta H^\circ = 133.0 \) kJ and \( \Delta S^\circ = 401.5 \) J/K
A) -252.6 kJ
B) -13.4 kJ
C) 13.4 kJ
D) 122.9 kJ
E) 252.6 kJ

91) . Given the following information, calculate \( \Delta G^\circ \) for the reaction below at 25°C:
\( 2 \text{H}_2\text{O}_2(\text{l}) \rightarrow 2 \text{H}_2\text{O}(\text{l}) + \text{O}_2(\text{g}) \)

<table>
<thead>
<tr>
<th>Compound</th>
<th>( \Delta H^\circ )(kJ/mol)</th>
<th>( S^\circ )(J/K·mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)O(_2)(l)</td>
<td>-187.8</td>
<td>109.6</td>
</tr>
<tr>
<td>H(_2)O(l)</td>
<td>-285.8</td>
<td>69.9</td>
</tr>
<tr>
<td>O(_2)(g)</td>
<td>-----</td>
<td>205.1</td>
</tr>
</tbody>
</table>

A) -37700 kJ
B) -342.6 kJ
C) -233.5 kJ
D) -257.3 kJ
E) -157.9 kJ
92) For the process at 25°C; I\(_2\) (g) → I\(_2\) (s); what are the signs of \(\Delta G\), \(\Delta H\), and \(\Delta S\)?

<table>
<thead>
<tr>
<th>(\Delta G)</th>
<th>(\Delta H)</th>
<th>(\Delta S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A)</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>B)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C)</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>D)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>E)</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

93) If a process is exothermic and not spontaneous, then what must be true?

A) \(\Delta S > 0\)
B) \(\Delta H > 0\)
C) \(\Delta G = 0\)
D) \(\Delta S < 0\)
E) \(\Delta H = 0\)

94) For any reaction at equilibrium, which of the following is true?

A) \(\Delta H < 0\)
B) \(\Delta S = 0\)
C) \(\Delta S < 0\)
D) \(\Delta H = 0\)
E) \(\Delta G = 0\)

95) All of the following have \(\Delta G^\circ = 0\) EXCEPT

A) O\(_2\) (g)
B) Br\(_2\) (g)
C) H\(_2\) (g)
D) Ca (s)
E) Hg (l)

96) Ammonium nitrate spontaneously dissolves in water at room temperature and the process causes the solution to become quite cold. Which of the following is TRUE about the dissolution of ammonium nitrate?

A) The process is exothermic.
B) Its solubility will be greater in warmer water.
C) \(\Delta S^\circ\) for the reaction is negative.
D) All solutions of ammonium nitrate are supersaturated.
E) All solutions of ammonium nitrate are cold.
Conceptual questions: All sections

1*) Cu(s) + 2 Ag⁺ ↔ Cu²⁺ + 2 Ag(s)

If the equilibrium constant for the reaction above is $3.7 \times 10^{15}$, which of the following correctly describes the standard voltage, $E^°$, and the standard free energy change, $ΔG^°$, for this reaction? (could be in electrochemistry too, $ΔG^° = -nFE^0$)

(A) $E^°$ is positive and $ΔG^°$ is negative.
(B) $E^°$ is negative and $ΔG^°$ is positive.
(C) $E^°$ and $ΔG^°$ are both positive.
(D) $E^°$ and $ΔG^°$ are both negative.
(E) $E^°$ and $ΔG^°$ are both zero

2) CH₄(g) + 2 O₂(g) ---→ CO₂(g) + 2 H₂O(l); $ΔH = -889.1$ kJ
$ΔH_f^°$ H₂O(l) = -285.8 kJ / mole
$ΔH_f^°$ CO₂(g) = -393.3 kJ / mole
What is the standard heat of formation of methane, $ΔH_f^°$ CH₄(g), as calculated from the data above?

(A) -210.0 kJ/mole
(B) -107.5 kJ/mole
(C) -75.8 kJ/mole
(D) 75.8 kJ/mole
(E) 210.0 kJ/mole

3) A cube of ice is added to some hot water in a rigid, insulated container, which is then sealed. There is no heat exchange with the surroundings. What has happened to the total energy and the total entropy when the system reaches equilibrium?

<table>
<thead>
<tr>
<th>Energy</th>
<th>Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Remains constant</td>
<td>Remains constant</td>
</tr>
<tr>
<td>(B) Remains constant</td>
<td>Decreases</td>
</tr>
<tr>
<td>(C) Remains constant</td>
<td>Increases</td>
</tr>
<tr>
<td>(D) Decreases</td>
<td>Increases</td>
</tr>
<tr>
<td>(E) Increases</td>
<td>Decreases</td>
</tr>
</tbody>
</table>

4) For the reaction A(g) ↔ B(g) + C(g), the equilibrium constant, $K_p$, is $2 \times 10^{-4}$ at 25 °C. A mixture of the three gases at 25 °C is placed in a reaction flask and the initial pressures are $P_A = 2$ atmosphere, $P_B = 0.5$ atmosphere, and $P_C = 1$ atmosphere, At the instant of mixing, which of the following is true for the reaction as written?

(A) $ΔG < 0$
(B) $ΔG > 0$
(C) $ΔS = 0$
(D) $ΔG^° = 0$
(E) $ΔG^° < 0$
5) The cooling curve for a pure substance as it changes from a liquid to a solid is shown below. The solid and the liquid coexist at

(A) point Q only
(B) point R only
(C) all points on the curve between Q and S
(D) all points on the curve between R and T
(E) no point on the curve

6) When solid ammonium chloride, NH₄Cl(s) is added to water at 25 °C, it dissolves and the temperature of the solution decreases. Which of the following is true for the values of ΔH and ΔS for the dissolving process?

<table>
<thead>
<tr>
<th>ΔH</th>
<th>ΔS</th>
</tr>
</thead>
<tbody>
<tr>
<td>A)</td>
<td>Positive Positive</td>
</tr>
<tr>
<td>B)</td>
<td>Positive Negative</td>
</tr>
<tr>
<td>C)</td>
<td>Positive Equal to zero</td>
</tr>
<tr>
<td>D)</td>
<td>Negative Positive</td>
</tr>
<tr>
<td>E)</td>
<td>Negative Negative</td>
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</table>

7) H₂(g) + 1/2 O₂(g) ---> H₂O(l) \( \Delta H^o = x \)
2 Na(s) + 1/2 O₂(g) ---> Na₂O(s) \( \Delta H^o = y \)
Na(s) + 1/2 O₂(g) + 1/2 H₂(g) ---> NaOH(s) \( \Delta H^o = z \)

Based on the information above, what is the standard enthalpy change for the following reaction?
Na₂O(s) + H₂O(l) ---> 2 NaOH(s)

(A) \( x + y + z \)
(B) \( x + y - z \)
(C) \( x + y - 2z \)
(D) \( 2z - x - y \)
(E) \( z - x - y \)
8) For which of the following processes would \( \Delta S \) have a negative value?

I. \( 2 \text{Fe}_2\text{O}_3(s) \rightarrow 4 \text{Fe}(s) + 3 \text{O}_2(g) \)
II. \( \text{Mg}^{2+} + 2 \text{OH}^- \rightarrow \text{Mg(OH)}_2(s) \)
III. \( \text{H}_2(g) + \text{C}_2\text{H}_4(g) \rightarrow 3 \text{C}_2\text{H}_6(g) \)

(A) I only
(B) I and II only
(C) I and III only
(D) II and III only
(E) I, II, and III

9) \( \text{N}_2(g) + 3 \text{H}_2(g) \rightarrow 2 \text{NH}_3(g) \)
The reaction indicated above is thermodynamically spontaneous at 298 K, but becomes nonspontaneous at higher temperatures. Which of the following is true at 298 K?

(A) \( \Delta G, \Delta H, \) and \( \Delta S \) are all positive.
(B) \( \Delta G, \Delta H, \) and \( \Delta S \) are all negative.
(C) \( \Delta G, \Delta H \) are negative, but \( \Delta S \) is positive.
(D) \( \Delta G \) and \( \Delta S \) are negative, but \( \Delta H \) is positive.
(E) \( \Delta G \) and \( \Delta H \) are positive, but \( \Delta S \) is negative

10) \( \text{I}_2(g) + 3 \text{Cl}_2(g) \rightarrow 2 \text{ICl}_3(g) \)
According to the data in the table below, what is the value of \( \Delta H^\circ \) for the reaction represented above?

<table>
<thead>
<tr>
<th>Bond</th>
<th>Average Bond Energy (kilojoules / mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I---I</td>
<td>149</td>
</tr>
<tr>
<td>Cl---Cl</td>
<td>239</td>
</tr>
<tr>
<td>I---Cl</td>
<td>208</td>
</tr>
</tbody>
</table>

(A) - 860 kJ
(B) - 382 kJ
(C) + 180 kJ
(D) + 450 kJ
(E) + 1,248 kJ

11) For the reaction of ethylene represented above, \( \Delta H \) is - 1,323 kJ. What is the value of \( \Delta H \) if the combustion produced liquid water \( \text{H}_2\text{O}(l) \), rather than water vapor \( \text{H}_2\text{O}(g) \)? (\( \Delta H \) for the phase change \( \text{H}_2\text{O}(g) \rightarrow \text{H}_2\text{O}(l) \) is -44 kJ mol\(^{-1}\).)

A) -1,235 kJ
B) -1,279 kJ
C) -1,323 kJ
D) -1,367 kJ
12) Which of the following reactions has the largest positive value of $\Delta S$ per mole of Cl$_2$?

(A) H$_2$(g) + Cl$_2$(g) $\rightarrow$ 2 HCl(g)
(B) Cl$_2$(g) + 1/2 O$_2$(g) $\rightarrow$ Cl$_2$O(g)
(C) Mg(s) + Cl$_2$(g) $\rightarrow$ MgCl$_2$(s)
(D) 2 NH$_4$Cl(s) $\rightarrow$ N$_2$(g) + 4 H$_2$(g) + Cl$_2$(g)
(E) Cl$_2$(g) $\rightarrow$ 2 Cl(g)

13) Which of the following must be true for a reaction that proceeds spontaneously from initial standard state conditions?

(A) $\Delta G^\circ > 0$ and $K_{eq} > 1$
(B) $\Delta G^\circ > 0$ and $K_{eq} < 1$
(C) $\Delta G^\circ < 0$ and $K_{eq} > 1$
(D) $\Delta G^\circ < 0$ and $K_{eq} > 1$
(E) $\Delta G^\circ = 0$ and $K_{eq} = 1$

14. H$_2$O(s) $\rightarrow$ H$_2$O(l) When ice melts at its normal melting point, 273.16 K and 1 atmosphere, which of the following is true for the process shown above?

(A) $\Delta H < 0$, $\Delta S > 0$, $\Delta V > 0$
(B) $\Delta H < 0$, $\Delta S < 0$, $\Delta V > 0$
(C) $\Delta H > 0$, $\Delta S < 0$, $\Delta V < 0$
(D) $\Delta H > 0$, $\Delta S > 0$, $\Delta V > 0$
(E) $\Delta H > 0$, $\Delta S > 0$, $\Delta V < 0$

Questions 15-17 refer to the following.

A) $\Delta H>0$, $\Delta S>0$
B) $\Delta H>0$, $\Delta S<0$
C) $\Delta H<0$, $\Delta S>0$
D) $\Delta H<0$, $\Delta S<0$
E) $\Delta H=0$, $\Delta S<0$

15) Must be true for a reaction that is spontaneous at all temperatures

16) True for the vaporization of liquid pentane

17) True for the combustion of liquid pentane, C$_5$H$_{12}$ (l), to form H$_2$O(g) and CO$_2$ (g) at 1 atm.
18) A quantity that would be zero for a pure, perfect crystal at 0K
   A) Activation energy
   B) Enthalpy of formation
   C) Entropy
   D) Gibbs free energy
   E) Lattice energy

19) The cooling curve above shows how the temperature of a sample varies with time as the sample goes through phase changes. The sample starts as a gas, and heat is removed at a constant rate. At which time does the sample contain the most liquid?

A) T1
B) T2
C) T3
D) T4
E) T5
20) The graph shows the temperature of a pure substance as it is heated at a constant rate in an open vessel at 1.0 atm pressure. The substance changes from solid to the liquid to the gas phase.

The substance is at its normal freezing point at time
A) T1  
B) T2  
C) T3  
D) T4  
E) T5

21) Which of the following best describes what happens to the substance between T4 and T5
A) The molecules are leaving the liquid phase  
B) The solid and liquid coexist in equilibrium  
C) The vapor pressure of the substance is decreasing  
D) The average intermolecular distance is decreasing  
E) The temperature of the substance is increasing

22) What is the standard enthalpy change, ΔH°, for the reaction represented above?
ΔH° f of C<sub>2</sub>H<sub>2</sub>(g) is 230kJ/mol  
ΔH° f of C<sub>6</sub>H<sub>6</sub>(g) is 83kJ/mol
A) -607kJ  
B) -147kJ  
C) -19kJ  
D) +19kJ  
E) +773kJ
23) When solid NH$_4$SCN is mixed with solid Ba(OH)$_2$ in a closed container, the temperature drops and a gas is produced. Which one of the following indicates the correct signs for free energy, enthalpy and entropy change.

<table>
<thead>
<tr>
<th>ΔG</th>
<th>ΔH</th>
<th>ΔS</th>
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<tbody>
<tr>
<td>A)</td>
<td>-</td>
<td>-</td>
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<td>B)</td>
<td>-</td>
<td>+</td>
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<tr>
<td>C)</td>
<td>-</td>
<td>+</td>
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<tr>
<td>D)</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>E)</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

24) Which of the following is true for a reaction in which the activation energy is the same for forward and backward reaction?
A) A catalyst present
B) The reaction order can be obtained directly from the balanced equation
C) The reaction order is zero
D) ΔH for the reaction is zero
E) ΔS for the reaction is zero

25) $X(s) \leftrightarrow X(l)$
Which of the following is true for any substance undergoing the above change at its normal melting point?
A) ΔS < 0
B) ΔH = 0
C) ΔH = TΔG
D) TΔS = 0
E) ΔH = TΔS

26) What is the value of $\Delta H^\circ$ (in kJ) for this reaction? $\Delta H^\circ$ for CuO = -156kJ/mol; $\Delta H^\circ$ Cu$_2$O = 170.7kJ

$2\text{CuO(s)} \leftrightarrow \text{Cu}_2\text{O(s)} + \frac{1}{2}\text{O}_2 (g)$
A) 141.5
B) 14.6
C) -14.6
D) -141.5
E) +1.46

27) For a reaction at 27 °C, $\Delta G^\circ = -35$ kJ and $\Delta S^\circ = -200$ J·K$^{-1}$, What is the value of $\Delta H$?
A) -95 kJ
B) +95 kJ
C) -25 kJ
D) 25. kJ
E) -60035 J
28) The standard enthalpy of formation for NH₃ (g) is −46.1 kJ.mol⁻¹. Calculate \( \Delta H^\circ \) for the reaction: \( 2\text{NH}_3 \ (g) \leftrightarrow \text{N}_2 \ (g) + 3\text{H}_2(g) \)

(A) −92.2 kJ
(B) −46.1 kJ
(C) 46.1 kJ
(D) 92.2 kJ
(E) 922 kJ

29) Which is always true for a specific system during a spontaneous reaction?

(A) \( \Delta H < 0 \)
(B) \( \Delta H \geq 0 \)
(C) \( \Delta G < 0 \)
(D) \( \Delta S > 0 \)
(E) \( \Delta G = 0 \)

30) Which equation represents the reaction for the standard enthalpy of formation, \( \Delta H^\circ \), for \( \text{B}_5\text{H}_9 \ (g) \) at 298 K and 1 atm?

(A) \( 5\text{B}(s) + 9\text{H}_2(g) \rightarrow \text{B}_5\text{H}_9(g) \)
(B) \( 2\text{B}(s) + 3\text{BH}_3(g) \rightarrow \text{B}_5\text{H}_9(g) \)
(C) \( 5/2 \text{B}_2(g) + 9/2\text{H}_2(g) \rightarrow \text{B}_5\text{H}_9(g) \)
(D) \( 5\text{B}(s) + 9/2\text{H}_2(g) \rightarrow \text{B}_5\text{H}_9(g) \)

31) \( \text{C}_2\text{H}_6(g) + 7/2\text{O}_2(g) \rightarrow 2\text{CO}_2(g) + 3\text{H}_2\text{O}(g) \) \( \Delta H^\circ = −1427.7 \) kJ. If the enthalpy of vaporization of \( \text{H}_2\text{O}(l) \) is 44.0 kJ/mol, what is the enthalpy for this reaction if water liquid is formed instead of \( \text{H}_2\text{O}(g) \).

(A) −1295.7 kJ
(B) −1383.7 kJ
(C) −1471.7 kJ
(D) −1559.7 kJ

32) Calculate the change in enthalpy, \( \Delta H \), for the combustion of 11.2 L of hydrogen gas, measured at 0 °C and 1 atm pressure, to form \( \text{H}_2\text{O}(g) \).

\[ \text{H}_2\text{O}(g) \ \Delta H^\circ = -241.8 \text{kJ/mol} \]

(A) −60.5 kJ
(B) −121 kJ
(C) −484 kJ
(D) −2710 kJ

33) Which reaction proceeds with the greatest increase in entropy?

(A) \( \text{H}_2(g) + \text{O}_2(g) \rightarrow \text{H}_2\text{O}_2(l) \)
(B) \( \text{Br}_2(l) + \text{F}_2(g) \rightarrow 2\text{BrF}(g) \)
(C) \( \text{Cu}^{2+}(aq) + \text{Zn}(s) \rightarrow \text{Cu}(s) + \text{Zn}^{2+}(aq) \)
(D) \( 4\text{NH}_3(g) + 7\text{O}_2(g) \rightarrow 4\text{NO}_2(g) + 6\text{H}_2\text{O}(g) \)
34) For the reaction, \( \text{N}_2\text{H}_4(\text{l}) \rightarrow \text{N}_2(\text{g}) + 2\text{H}_2(\text{g}) \) \( \Delta H^\circ = -50.6 \text{ kJ} \). This reaction is
   A) (A) spontaneous at all temperatures.
   B) (B) non-spontaneous at all temperatures.
   C) (C) spontaneous only at low temperatures.
   D) (D) spontaneous only at high temperatures.

35) For the reaction shown, which is closest to the value of \( \Delta H \)?
2\( \text{Cr}^{3+}(\text{aq}) + 3\text{Ni}(\text{s}) \rightarrow 2\text{Cr}(\text{s}) + 3\text{Ni}^{2+}(\text{aq}) \)
\( \Delta H^\circ_{\text{Cr}^{3+}} = -143\text{kJ/mol}; \quad \Delta H^\circ_{\text{Ni}^{2+}} = -54\text{kJ/mol} \)
   A) 124 kJ
   B) 89 kJ
   C) -89 kJ
   D) -124 kJ
### Answers

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### Conceptual questions : All sections

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Free-Response

Question 1
Acetylene gas, C\textsubscript{2}H\textsubscript{2}, is used in gas welding procedures and is a very important commercial gas. Use the data below to answer the following questions about the combustion of acetylene gas. Assume all reactions occur at 25°C.

<table>
<thead>
<tr>
<th>Substance</th>
<th>(\Delta H^\circ) (kJ mol(^{-1}))</th>
<th>(S^\circ) (J mol(^{-1}) K(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{2}H\textsubscript{2} (g)</td>
<td>227</td>
<td>200.9</td>
</tr>
<tr>
<td>O\textsubscript{2} (g)</td>
<td>0</td>
<td>205</td>
</tr>
<tr>
<td>CO\textsubscript{2} (g)</td>
<td>-393.5</td>
<td>213.7</td>
</tr>
<tr>
<td>H\textsubscript{2}O (l)</td>
<td>-285.8</td>
<td>69.9</td>
</tr>
</tbody>
</table>

(a) Write a complete balanced chemical equation for the combustion of acetylene, C\textsubscript{2}H\textsubscript{2}. Assume that CO\textsubscript{2} (g) and H\textsubscript{2}O (l) are the only products.

(b) Calculate the standard enthalpy change, \(\Delta H^\circ\), for the combustion of acetylene.

(c) Calculate the standard entropy change, \(\Delta S^\circ\), for the combustion of acetylene.

(d) Determine the value of \(\Delta G^\circ\) for the reaction.

(e) If 1 mol of C\textsubscript{2}H\textsubscript{2} is burned and all of the evolved heat is used to heat 6.00 kg of pure water, what will be the temperature change of the water? The specific heat of water is 4.18 Jg\(^{-1}\)K\(^{-1}\).

Question 2

(a) An ice cube is placed in a flask at room temperature and allowed to sit until the temperature of the water in the flask has reached room temperature. Describe the changes in enthalpy, entropy, free energy, and temperature that occur during the time interval.

(b) 40.0 g of sodium hydroxide pellets are added to 50.0 mL of water and most of it dissolves very quickly. The temperature of the system increases. Describe the changes in enthalpy, entropy, and free energy during this process.

(c) Commercial instant ice packs are available that contain a mixture of ammonium nitrate and water separated by a barrier. When the ice pack is twisted, the barrier breaks and the two substances mix. The temperature rapidly decreases as the ammonium nitrate dissolves in the water. Describe the changes in enthalpy, entropy, and free energy during this process.

Question 3

\[ \text{N}_2 (g) + 3\text{H}_2 (g) \rightarrow 2\text{NH}_3 (g) \]

The heat of formation, \(\Delta H^\circ\) of NH\textsubscript{3} (g) is -46.2 kJ/mol. The free energy of formation, \(\Delta G^\circ\) of NH\textsubscript{3}(g) is -16.7 kJ/mol.

(a) What are the values of \(\Delta H^\circ\) and \(\Delta G^\circ\) for the reaction above?

(b) What is the value of the entropy change, \(\Delta S^\circ\), for the reaction above at 298 K?

(c) As the temperature is increased, what is the effect on G for the reaction? How does this affect the spontaneity of the reaction?
(d) At what temperature can \( \text{N}_2, \text{H}_2 \) and \( \text{NH}_3 \) gases be maintained together in equilibrium, each with a partial pressure of 1 atm?
Question 4

2 H₂ (g) + O₂ (g) → 2 H₂O (l)

The reaction above proceeds spontaneously from standard conditions at 298 K.

(a) Predict the sign of the entropy change, ∆S°, for the reaction. Explain.
(b) How would the value of ∆S° for the reaction change if the product of the reaction was H₂O (g)?
(c) What is the sign of ∆G° at 298 K? Explain.
(d) What is the sign of ∆H° at 298 K? Explain.

Question 5

CaO (s) + CO₂ (g) → CaCO₃ (s)

The reaction above is spontaneous at 298 K and the heat of reaction, ∆H°, is -178 kJ.

(a) Predict the sign of the entropy change, ∆S°, for the reaction. Explain.
(b) What is the sign of ∆G° at 298 K? Explain.
(c) What change, if any, occurs to the value of ∆G° as the temperature is increased from 298 K?
(d) As the reaction takes place in a closed container, what changes will occur in the concentration of CO₂ and the temperature?

Question 6

<table>
<thead>
<tr>
<th>Substance</th>
<th>Enthalpy of Combustion, ∆H° Kilojoules/mole</th>
<th>Absolute Entropy, S° Joules/mole·K</th>
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</thead>
<tbody>
<tr>
<td>C(s)</td>
<td>-393.5</td>
<td>5.740</td>
</tr>
<tr>
<td>H₂ (g)</td>
<td>-285.8</td>
<td>130.6</td>
</tr>
<tr>
<td>C₂H₅OH (l)</td>
<td>-1366.7</td>
<td>160.7</td>
</tr>
<tr>
<td>H₂O (l)</td>
<td>-------------------------------</td>
<td>69.91</td>
</tr>
</tbody>
</table>

(a) Write a separate, balanced chemical equation for the combustion of each of the following: C(s), H₂ (g), and C₂H₅OH (l). Consider the only products to be CO₂ (g) and/or H₂O (l).
(b) In principle, ethanol can be prepared by the following reaction:

\[ 2 \text{C (s)} + 2 \text{H₂ (g)} + 2 \text{H₂O (l)} \rightarrow \text{C₂H₅OH (l)} \]

Calculate the standard enthalpy change, ∆H°, for the preparation of ethanol, as shown in the reaction above.
(c) Calculate the standard entropy change, ∆S°, for the reaction given in part (b).
(d) Calculate the value of the equilibrium constant at 25°C for the reaction represented by the equation in part (b).
Question 7

BCl₃(g) + NH₃(g) ↔ Cl₃BNH₃(s)

The reaction represented above is a reversible reaction.

(a) Predict the sign of the entropy change, ΔS°, as the reaction proceeds to the right. Explain your prediction.

(b) If the reaction proceeds spontaneously to the right, predict the sign of the enthalpy change, ΔH°. Explain your prediction.

(c) The direction in which the reaction proceeds spontaneously changes as the temperature is increased above a specific temperature. Explain why.

(d) What is the value of the equilibrium constant at the temperature referred to in (c); that is, the specific temperature at which the direction of the spontaneous reaction changes? Explain.

Question 8

C₂H₂(g) + 2 H₂(g) → C₂H₆(g)

Information about the substances involved in the reaction represented above is summarized in the following tables.

<table>
<thead>
<tr>
<th>Substance</th>
<th>ΔH°f (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₂H₂(g)</td>
<td>226.7</td>
</tr>
<tr>
<td>C₂H₆(g)</td>
<td>-84.7</td>
</tr>
</tbody>
</table>

(a) Write the equation for the heat of formation of C₂H₆(g)

(b) Use the above information to determine the enthalpy of reaction for the equation given.

C₆H₅OH(s) + 7O₂(g) → 6CO₂(g) + 3H₂O(l)

When a 2.000-gram sample of pure phenol, C₆H₅OH(s), is completely burned according to the equation above, 64.98 kilojoules of heat is released. Use the information in the table below to answer the questions that follow.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Standard Heat of Formation, ΔH°f; at 25°C (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂(g)</td>
<td>-393.5</td>
</tr>
<tr>
<td>H₂O(l)</td>
<td>-285.85</td>
</tr>
<tr>
<td>C₆H₅OH(s)</td>
<td>?</td>
</tr>
</tbody>
</table>

c)  
   i. Calculate the molar heat of combustion of phenol in kilojoules per mole at 25°C.
   ii. Calculate the standard heat of formation, ΔH°f, of phenol in kilojoules per mole at 25°C.
**Question 9**
Answer the following question about thermodynamics.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Combustion Reaction</th>
<th>Enthalpy of Combustion, $\Delta H^\circ_{\text{comb}, , 298 , K}$ ($\text{kJ/mol}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$(g)</td>
<td>H$_2$(g) + $\frac{1}{2}$O$_2$(g) $\rightarrow$ H$_2$O(l)</td>
<td>-290</td>
</tr>
<tr>
<td>C(s)</td>
<td>C(s) + O$_2$(g) $\rightarrow$ CO$_2$(g)</td>
<td>-390</td>
</tr>
<tr>
<td>CH$_3$OH(l)</td>
<td></td>
<td>-730</td>
</tr>
</tbody>
</table>

a) In the empty box in the table above, write a balanced chemical equation for the complete combustion of one mole of CH$_3$OH (l). Assume products are in their standard states at 298 K. Coefficients do not need to be whole number.

b) On the basis of your answer to part (a) and the information in the table, determine the enthalpy change for the reaction:
$$\text{C (s) + H}_2\,(g) + \text{H}_2\text{O (l)} \rightarrow \text{CH}_3\text{OH (l)}$$

c) Write the balanced chemical equation that shows the reaction that is used to determine the enthalpy of formation for one mole of CH$_3$OH (l).

d) Predict the sign of $\Delta S$ for the combustion of H$_2$ (g). Explain your reasoning.

e) On the basis of bond energies, explain why the combustion of H$_2$ (g) is exothermic.

**Question 10**
Answer the following questions about the thermodynamics of the reactions represented below.

Reaction X: $\frac{1}{2}$I$_2$(s) + $\frac{1}{2}$Cl$_2$(g) $\leftrightarrow$ ICl(g) \hspace{1cm} $\Delta H_f = 18 \, \text{kJ/mol}, \hspace{1cm} \Delta S_{298} = 78 \, \text{J/K·mol}$

Reaction Y: $\frac{1}{2}$I$_2$(s) + $\frac{1}{2}$Br$_2$(l) $\leftrightarrow$ IBr(g) \hspace{1cm} $\Delta H_f = 41 \, \text{kJ/mol}, \hspace{1cm} \Delta S_{298} = 124 \, \text{J/K·mol}$

a) Is reaction X, represented above, spontaneous under standard conditions? Justify your answer with a calculation.

b) Calculate the value of the equilibrium constant, $K_{eq}$, for reaction X at 25°C.

c) What effect will an increase in temperature have on the equilibrium constant for reaction X? Explain your answer.

d) Explain why the standard entropy change is greater for reaction Y than for reaction X.

e) Above what temperature will the value of the equilibrium constant for reaction Y be greater than 1.0? Justify your answer with calculations.

f) For the vaporization of solid iodine, I$_2$ (s) $\rightarrow$ I$_2$ (g), the value of $\Delta H_{298}$ is 62 kJ mol$^{-1}$. Using this information, calculate the value of $\Delta H_{298}$ for the reaction represented below.

$$I_2(g) + Cl_2(g) \leftrightarrow 2ICl(g)$$
Free Response Answers:

Question 1
a. \(2\text{C}_2\text{H}_2 + 5\text{O}_2 \rightarrow 4\text{CO}_2 + 2\text{H}_2\text{O}\)
b. \(\Delta H° = \Delta H_\text{pd}° - \Delta H_\text{rct}°\)
   \[= [(4x(-393.5)) + 2(-285.8)] - (2x227)\]
   \[= 2602.6 \text{ kJ} / 2 \text{ (b/c there are 2 moles)} = -1301\]
c. \(\Delta S° = \Delta S_\text{pd}° - \Delta S_\text{rct}° = -432/2 \text{ (b/c there are 2 moles)} = -216 \text{ J/mol-K}\)
d. \(\Delta G° = \Delta H° - T\Delta S° = -1237 \text{ kJ}\)
e. \(\Delta H° \text{ from (b) = 2602.6 kJ for two moles undergoing combustion}\)
   \[\Delta T = 1301300J/(6000)(4.18) = 51.8K\]

Question 2
a. Ice cube melts right away
   \(\Delta H\) — endothermic: +\(\Delta H\)  
   \(\Delta S\) — solid \(\rightarrow\) liquid: +\(\Delta S\)  
   \(\Delta G\) — (\(\cdot\)): spontaneous  
   \(T\) — Increases
b. 40 g NaOH dissolves in 50 mL \(\text{H}_2\text{O}\)
   \(\Delta H\) = exothermic (-)  
   \(\Delta S\) = increases (+)  
   \(\Delta G\) = spontaneous (-)
c. \(\Delta H\) = endothermic (+)  
   \(\Delta S\) = increases (+)  
   \(\Delta G\) = spontaneous (-)

Question 3
\(\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3\)
\(\Delta H°\) of \(\text{NH}_3\) = -46.2 kJ/mol  
\(\Delta G°\) of \(\text{NH}_3\) = -16.7 kJ/mol
a. \(\Delta H_\text{rxn}° = \text{Product} - \text{Reactants}\)
   \[= 2x(-46.2) = -92.4 \text{ kJ}\]
   \(\Delta G_\text{rxn}° = 2(-16.7) = -33.4 \text{ kJ}\)
b. \(\Delta S_\text{rxn}° : \Delta G = \Delta H - T\Delta S\)
   \(\Delta S = (\Delta H - \Delta G) / T\)
   \(\Delta S = -0.197 \text{ kJ}\)
c. \(\Delta G = \Delta H - T\Delta S\)
   (-) (\(\cdot\)) (-)
   As the temperature increases, \(T \Delta S\) becomes more (+) and \(\Delta G\) becomes less negative. The reaction will become less spontaneous at high temperatures.
d. At equilibrium, \(\Delta G = 0\).
   \(T = \Delta H / \Delta S = 469 \text{ K}\)
Question 4

2H\(_2\) (g) + O\(_2\) (g) → 2H\(_2\)O(l)

Spontaneous at 298K

a. \(\Delta S\) (·) : gas → liquid
   \(\Delta G\) (·) : Reaction is spontaneous

b. The \(\Delta S_{rxn}\) would increase if the product was H\(_2\)O(g) instead of H\(_2\)O(l). So \(\Delta S\) becomes more (+).

c. \(\Delta G\) (-)

d. \(\Delta G = \Delta H - T\Delta S\); \(\Delta H\) should be (-). Since \(\Delta S\) is not the driving force, the \(R_x\) should be exothermic to make it spontaneous.

Question 5

CaO(s) + CO\(_2\) (g) → CaCO\(_3\) (s)

Spontaneous at 298 K, \(\Delta H^\circ = -178\) kJ

a. \(\Delta S\) : (-)

b. \(\Delta G\) : (-) [spontaneous]

c. \(\Delta G = \Delta H - T\Delta S\)
   (-) (-) (-)

\(\Delta H\) and \(\Delta S\) are both (-). The reaction will be spontaneous at low temperatures. As the temperature increases, the reaction will become nonspontaneous.

d. [CO\(_2\)] decreases and T increases. As the reaction proceeds in the forward direction, the reactants are consumed.

Question 6

a. C + O\(_2\) → CO\(_2\)  [1]

2H\(_2\) + O\(_2\) → 2H\(_2\)O  [2]

C\(_2\)H\(_5\)OH + 3O\(_2\) → 2CO\(_2\) + 3H\(_2\)O  [3]

b. eq (1) x 2 + eq (2) + Rev eq (3)

2C + 2O\(_2\) → 2CO\(_2\)
2H\(_2\) + O\(_2\) → 2H\(_2\)O
2CO\(_2\) + 3H\(_2\)O → C\(_2\)H\(_5\)OH + 3O\(_2\)
2C(s) + 2H\(_2\)(g) + 2H\(_2\)O(l) → C\(_2\)H\(_5\)OH (l)

\(\Delta H = +8.1\) kJ


d. \(\Delta G = \Delta H - T\Delta S = 8100 - (298)(-181.9)J = 62300J\)

\(K_{eq} = e^{\Delta G/RT} = e^{-(62300/8.314 \times 298)} = 1.2 \times 10^{-11}\)
Question 7

a. Because a mixture of two gases produces a single solid product, there is an extremely large decrease in entropy, therefore $\Delta S > 0$, ie, the sign of $\Delta S$ is negative.

b. In order for a spontaneous change to occur to the right direction, the enthalpy change must overcome the entropy change which favors the reactants, since nature favors a lower enthalpy, then the reaction must be exothermic to the right. Therefore $\Delta H < 0$.

c. $\Delta G = \Delta H - T\Delta S$, the reaction will change direction when the sign of $\Delta G$ changes, since $\Delta H < 0$ and $\Delta S < 0$, then at low temperatures, the sign of $\Delta G$ is negative and spontaneous to the right. At some point higher $T$, $\Delta H = T\Delta S$ and $\Delta G = 0$, thereafter, any higher temperature will see $\Delta G$ as positive and spontaneous in the left direction.

d. At equilibrium, $K = e^{-\Delta G/RT}$, where $\Delta G = 0$, $K = e^0 = 1$

Question 8

a. $2C$(graphite) + $3H_2(g) \rightarrow C_2H_6(g)$

b. $\Delta H_{\text{rxn}} = -84.7 - 226.7 = -311.4 \text{ kJ}$

c. 
   i. $2.00 g \text{ C}_6\text{H}_5\text{OH}/94 \text{ g.mol} \text{ C}_6\text{H}_5\text{OH} = 0.02128 \text{ mol C}_6\text{H}_5\text{OH}$
      $\Delta H = 64.98 \text{ kJ}/0.02128 \text{ mol} = 3054 \text{ kJ/mol}$
   ii. $\Delta H = \Delta H_{pd} - \Delta H_{rct} \rightarrow -3054 = 6(-393.5) + 3(-385.5) - x$
       $x = -164.5 \text{ kJ/mol}$

Question 9

a. $\text{CH}_3\text{OH}(l) + 3/2\text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(l)$

b. $\text{C(s)} + \text{O}_2(g) \rightarrow \text{CO}_2(g)$
   $\text{H}_2(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{O}(l)$
   $\text{CO}_2(g) + 2\text{H}_2\text{O}(l) \rightarrow \text{CH}_3\text{OH}(l) + 3/2\text{O}_2(g)$
   $\text{CH}_3\text{OH}(l) + 3/2\text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(l)$
   $\text{C(s)} + 1/2\text{O}_2(g) + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH}(l)$

   $\Delta S < 0$ start with gas phase reactants, end with liquid phase products; product more ordered.

d. $\Delta S < 0$ start with gas phase reactants, end with liquid phase products; product more ordered.

e. The combustion of H2 is exothermic because more energy is released during the formation of two mole of O-H bonds than is required to break one mole of H-H bonds and one-half mole of O-O bonds.
Question 10

a. \[ \Delta G^\circ = \Delta H^\circ - T\Delta S^\circ = (18 \text{ kJ mol}^{-1}) - (298 \text{ K})(0.078 \text{ kJ mol}^{-1}) = -5 \text{ kJ mol}^{-1} \]

Reaction is spontaneous because \( \Delta G^\circ < 0 \).

b. \[ \Delta G^\circ = -RT \ln K_{eq} \]

\[
\ln K_{eq} = \frac{(-5 \times 10^3)}{(8.31)(298)} = 2.019
\]

\[ K_{eq} = e^{2.019} = 0.132 \]

c. \[ \Delta G^\circ = -RT \ln K_{eq} = \Delta H^\circ - T\Delta S^\circ \]

Since \( \Delta H^\circ \) is positive, an increase in \( T \) will cause \(- \Delta H^\circ/RT\) to become a smaller negative number, therefore \( K_{eq} \) will increase.

OR

The reaction is endothermic (\( \Delta H^\circ = +18 \text{ kJ mol}^{-1} \)); an increase in temperature shifts the reaction to favor more products relative to the reactants, resulting in an increase in the value of \( K_{eq} \).

d. Both reaction \( X \) and reaction \( Y \) have solid iodine as a reactant, but the second reactant in reaction \( X \) is chlorine gas whereas the second reactant in reaction \( Y \) is liquid bromine. Liquids have lower entropies than gases, thus in reaction \( Y \) the reactants are more ordered (and have lower entropies) than in reaction \( X \). The products of both reaction \( X \) and reaction \( Y \) have about the same disorder, so the change in entropy from reactants to products is greater in reaction \( Y \) than in reaction \( X \).

e. \[ \Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \]

\[ K_{eq} = 1 \text{ when } \Delta G^\circ = 0 \Rightarrow T\Delta S^\circ = \Delta H^\circ \rightarrow T = 330 \text{ K} \]

So when \( T > 330 \text{ K} \), \( \Delta G^\circ < 0 \text{ kJ mol}^{-1} \rightarrow K_{eq} > 1.0 \)

f. \[ \begin{align*}
I_2(s) + Cl_2(g) & \leftrightarrow 2ICl(g) & \Delta H_{298} = 2 \times 18 \text{ kJ/mol} \\
I_2(g) & \leftrightarrow I_2(s) & \Delta H_{298} = -62 \text{ kJ/mol} \\
I_2(g) + Cl_2(g) & \leftrightarrow 2ICl(g) & \Delta H_{298} = -26 \text{ kJ/mol}
\end{align*} \]