LAST Name: ____

FIRST Name: ____

Student #: ____

CHM2132 Exam
Fall 2013

This is a closed book exam with no notes allowed. Non-graphing, non-programmable calculators are permitted. Data, constants and equations are provided on the last two pages of the exam. You may rip these 2 pages off of the exam and use them for rough work.

You must show all work to receive partial credit.

Remember to include units in all your calculations. **Marks will be deducted if units are not shown in your final answer. Marks will be deducted if an unreasonable number of sig figs is shown in final answer.**

If data calculated in previous sections of a multi-part question and used for subsequent calculations is incorrect, no additional mark deductions will be applied.

Q1: __________/10 Q2: __________/10 Q3: __________/11 Q4: __________/10

Q5: __________/12 Q6: __________/10 Q7: __________/9 Q8: __________/11

Q9: __________/6 Q10: __________/5 Q11: __________/6

Total = __________/100

Question 1. Answer **<u>10 of the following 11</u>** questions (1 mark each)

a) Is a sealed glass tube containing a real gas an open, closed or isolated system?

Closed

b) If 1 mole of N_2 is isothermally introduced into a rigid-walled flsk containing 1 mole of H_2 at room temperature, will the partial pressure of H_2 increase, decrease, or stay the same?

Stays the same

c) What is the change in internal energy for a heat engine that releases 350 J of heat when 300 J of work is done on it?

-50 J

d) Is the process described for the heat engine in part c) physically possible if it absorbs 350 J of heat? Why or why not?

No, since less energy is put into it than it is releasing, which violates the first law of thermodynamics.

e) Circle all the term(s) below that do NOT represent a state function:

i) Gibbs energy ii) entropy [✓ iii) heat capacity] iv) enthalpy [✓ v) heat]

f) If the internal pressure (π_T) of a real gas is positive, are intermolecular interactions repulsive or attractive?

Attractive

g) If the internal pressure (π_T) of a real gas is positive, does the gas release or absorb heat when it expands freely ($p_{ext} = 0$)?

Heat is absorbed

h) For what type of process can Helmholtz energy calculations be used to find the maximum work that can be done by the system?

Isothermal

i) If a dissolved substance precipitates from solution, does the entropy of this substance increase or decrease?

Decreases

j) What equation from the equation sheet would you use to calculate the molar Gibbs energy of mixing for one component of a binary solution? (Just give the equation as it appears on the equation sheet.)

$$\boxed{\mu_i = \mu_i^* + RT\ln\left(a_i\right)} \quad \text{or} \quad \boxed{\mu_i = \mu_i^o + RT\ln\left(a_i\right)}$$

k) According to the Debye-Huckel model, is the chemical potential of an ion lower or higher than it would be if it were in an ideal solution?

Lower

Question 2. Answer <u>**5 of the following 6**</u> questions. (2 marks each)

a) Rank the three isothermal processes below performed at 298 K on 1 mole of an ideal gas in terms of magnitude of work from <u>smallest (1)</u> to <u>largest (3)</u>.

Rank:

irreversible compression from 4 L to 2 L ____3___

reversible expansion from 2 L to 4 L ____2___

irreversible expansion from 2 L to 4 L ____1____

b) Write the formation reaction for solid alanine ($C_3O_2H_7$). Be sure to include the phases in your equation.

$$3\,\mathrm{C}\,(s) + \mathrm{O_2}\,(g) + 7/2\,\mathrm{H_2}\,(g) \rightarrow \mathrm{C_3O_2H_7}\,(s)$$

c) Why is the enthalpy of vaporization always greater than the internal energy change for vaporization?

The internal energy change corresponds to the amount of energy required to disrupt intermolecular interactions in liquid to form the gas. Enthalpy reflects the internal energy change, plus the energy required for the gas to expand against the external atmosphere, (i.e. energy required to do work).

d) Is it possible to change the entropy of an ideal gas trapped inside a perfectly insulated sealed container? Why or why not?

Yes it is possible. Although the system is insulated, and therefore no heat energy transfer can occur, it is still possible to do work on this system. So long as this is not done via a reversible adiabatic path, then the entropy of the system will change. This can be calculated by finding a reversible path that connects the initial and final states, and using the heat from this reversible path to calculate the entropy change.

e) If a heat engine operating between 4.0°C and 100.0°C absorbs 55.0 kJ of heat, what is the maximum amount of work that can be done?

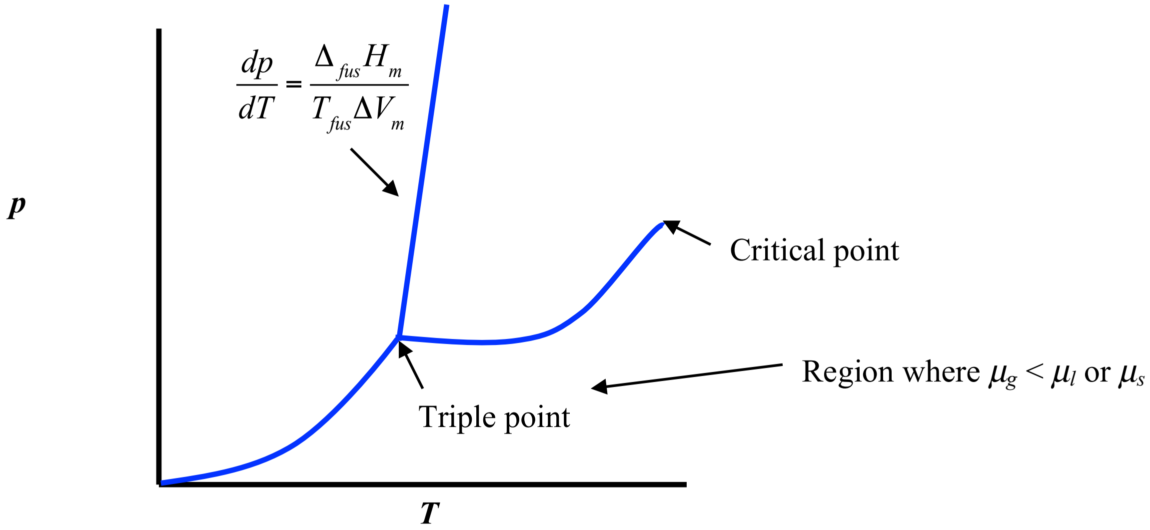
$$w_{\mathrm{max}} = (T_{\mathrm{high}} - T_{\mathrm{low}})/T_{\mathrm{high}} \text{ x } q = (100 - 4)\mathrm{K}/373\ \mathrm{K} \text{ x } 55\ \mathrm{kJ} = 14\ \mathrm{kJ}$$

f) Solve $\left(\frac{\partial p}{\partial T}\right)_V$ for a van der Waals gas.

$$\left(\frac{\partial p}{\partial T}\right)_V = \left(\frac{\partial\left(\frac{nRT}{V-nb} - a\left(\frac{n}{V}\right)^2\right)}{\partial T}\right)_V = \left(\frac{\partial\left(\frac{nRT}{V-nb}\right)}{\partial T}\right)_V - \left(\frac{\partial\left(a\left(\frac{n}{V}\right)^2\right)}{\partial T}\right)_V = \left(\frac{nR}{V-nb}\right)\left(\frac{\partial T}{\partial T}\right)_V = \frac{nR}{V-nb}$$

Question 3.

a) Sketch a phase diagram for a pure substance, and label the axes, triple point and critical point. Draw an arrow to the liquid-solid phase transition boundary and label it with the equation of this line. Indicate the region of the phase diagram where the chemical potential of the gas phase will be lower than the chemical potential of the other 2 phases. (6 marks)



b) Suppose a 5.450 g piece of ice is put into a 10.0 L freezer containing only dry air that is kept at -20.0°C. After the system is allowed to come to equilibrium, what will the new mass of the ice be? (5 marks)

$$\ln\left(\frac{p_2}{p_1}\right) = -\frac{\Delta H_{sub}}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)$$

$$\begin{aligned}\ln p_2 &= -\frac{\Delta H_{sub}}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)+\ln p_1\\ &= -\frac{46660\ \mathrm{J\ mol^{-1}}}{8.314\ \mathrm{J\ K^{-1}\ mol^{-1}}}\left(\frac{1}{253.15\ \mathrm{K}}-\frac{1}{273.16\ \mathrm{K}}\right)+\ln\left(611\ \mathrm{Pa}\right)\\ &= 4.78\\ p_2 &= 119\ \mathrm{Pa}\end{aligned}$$

$$\begin{aligned}m = nM &= \frac{pVM}{RT}\\ &= \frac{\left(119\ \mathrm{Pa}\right)\left(10.0\ \mathrm{L}\right)\left(10^{-3}\ \mathrm{m^3\ L^{-1}}\right)\left(18.01\ \mathrm{g\ mol^{-1}}\right)}{\left(8.314\ \mathrm{J\ K^{-1}\ mol^{-1}}\right)\left(253.15\ \mathrm{K}\right)}\\ &= 10.2\ \mathrm{mg}\end{aligned}$$

$$m_{\mathrm{final}} = \mathrm{m}_{\mathrm{initial}} - m_{\mathrm{lost}}$$

New mass of ice: $= 5.450\ \mathrm{g} - 0.0102\ \mathrm{g}$

$=5.440\ \mathrm{g}$

Question 4. Calculate the following for the combustion of phenol (C_6H_6O) in a bomb calorimeter at 298.15 K. (Bomb calorimeter means it is sealed, with rigid walls.) Some useful data is provided on page 12.

a) $\Delta H^o{}_m$ (3 marks)

$$C_6H_6O\,(s) + 7\,O_2\,(g) \rightarrow 6\,CO_2\,(g) + 3\,H_2O\,(l)$$

$$\begin{aligned}\Delta H_r^o &= 6\Delta H_f^o(CO_2) + 3\Delta H_f^o(H_2O) - \Delta H_f^o(C_6H_6O)\\ &= \left[6(-393.5) + 3(-285.8) - (-165.1)\right] \text{ kJ mol}^{-1}\\ &= -3053 \text{ kJ mol}^{-1}\end{aligned}$$

b) $\Delta S^o{}_m$. (1 mark)

$$\begin{aligned}\Delta S_r^o &= 6S_m^o(CO_2) + 3S_m^o(H_2O) - S_m^o(C_6H_6O) - 7S_m^o(O_2)\\ &= \left[6(213.8) + 3(70.0) - (1440) - 7(205.2)\right] \text{ J K}^{-1}\text{ mol}^{-1}\\ &= -87.6 \text{ J K}^{-1}\text{ mol}^{-1}\end{aligned}$$

c) $\Delta G^o{}_m$. (1 mark)

$$\begin{aligned}\Delta G_r^o &= \Delta H_r^o - T\Delta S_r^o\\ &= -3053 \text{ kJ mol}^{-1} - (298.15\text{ K})(-87.65\text{ J K}^{-1}\text{ mol}^{-1})(10^{-3}\text{ kJ J}^{-1})\\ &= -3027 \text{ kJ mol}^{-1}\end{aligned}$$

d) The heat of this reaction for 1 mol of phenol. (3 marks)

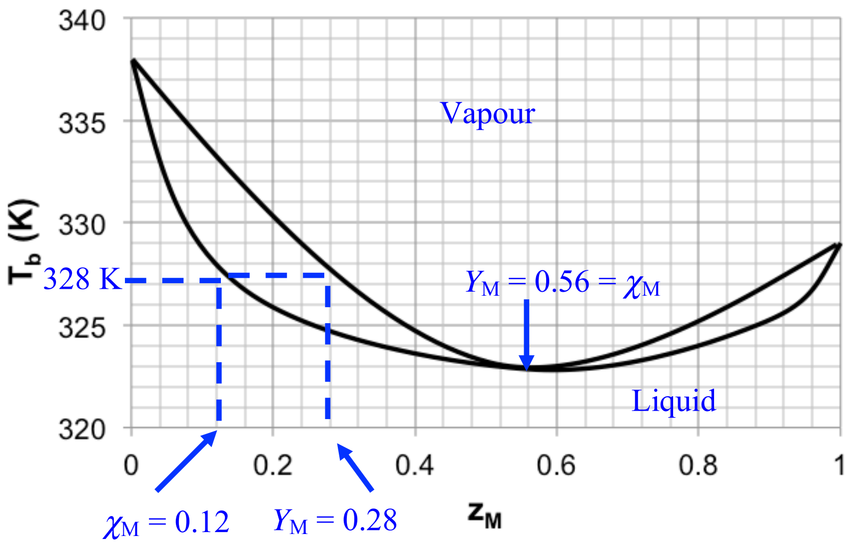
$$\begin{aligned}q = \Delta U_r^o &= \Delta H_r^o - \Delta(pV)\\ &= \Delta H_r^o - \Delta v RT\\ &= -3053 \text{ kJ mol}^{-1} - (-1)(-8.314\text{ J K}^{-1}\text{ mol}^{-1})(298.15\text{ K})(10^{-3}\text{ kJ J}^{-1})\\ &= -3050 \text{ kJ mol}^{-1}\end{aligned}$$

e) $\Delta G^o{}_m$ at 50°C. Assume that the reaction enthalpy is temperature independent. (2 marks)

$$\frac{\Delta G(T_2)}{T_2} = \frac{\Delta G(T_1)}{T_1} + \Delta H\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$\begin{aligned}\Delta G(T_2) &= (323\text{ K})\left[\frac{-3027\text{ kJ mol}^{-1}}{T_1} + (3053\text{ kJ mol}^{-1})\left(\frac{1}{323\text{ K}} - \frac{1}{298\text{ K}}\right)\right]\\ &= -3023 \text{ kJ mol}^{-1}\end{aligned}$$

Question 5. The normal boiling point of a methanol (M) – chloroform (C) solution was measured for a range of compositions to give the 2-component phase diagram shown below. (12 marks)



a) What is the boiling point of pure chloroform?

~338 K

b) Label the pure liquid and pure vapour regions of the phase diagram.

c) Is the boiling point of this real solution greater than or less than the boiling point would be for an ideal solution?

Less than ideal solution

d) Suppose 0.6 mol of methanol is added to 4.4 mol of chloroform. At what temperature will it begin to boil?

$\chi_M = 0.6$ mol / 5.0 mol = 0.12 $T_b \sim 328$ K

e) What is the composition of the vapour phase of the solution in d) when it just begins to boil?
$y_M = 0.28$

f) What is the composition of the vapour at the azeotrope?
$y_M = 0.56$

g) Which component is more volatile, methanol or chloroform?
Methanol

h) According to this phase diagram, do methanol and chloroform interact more favourably with each other, or with themselves? Justify your answer with ~1 sentence.
With themselves. The boiling point for any mixture of these two substances is lower than it would be in the ideal case. This lower boiling point reflects the fact that interactions in solution are weaker between methanol and chloroform compared to methanol to itself or chloroform to itself. Therefore less energy (and a lower temperature) is required for methanol and chloroform to escape from the liquid phase when they are mixed together.

i) Is it possible to isolate pure methanol from the solution made in d) by fractional distillation? Why or why not?
No. It can only distil to the azeotropic concentration – at that point the composition of the vapour phase is the same as that for the solution phase, and not further change in solution composition is possible.

Question 6. For the cell run at 298.15 K:

$$\text{Fe}\,(s)\,|\,\text{FeCl}_2\,(aq,\ a\pm = 0.0250)\,|\,\text{Hg}_2\text{Cl}_2\,(s)\,|\,\text{Hg}\,(l)$$

a) Write the balanced chemical equation that would result in the transfer of two molar equivalents of electrons. (3 marks)

Oxidation: $\text{Fe}\,(s) \rightarrow \text{Fe}^{2+}\,(aq) + 2\text{ e-}$

Reduction: $\underline{\text{Hg}_2\text{Cl}_2\,(s) + 2\text{ e-} \rightarrow 2\text{ Hg}\,(l) + 2\text{ Cl-}\,(aq)}$

Overall: $\text{Fe}\,(s) + \text{Hg}_2\text{Cl}_2\,(s) \rightarrow \text{Fe}^{2+}\,(aq) + 2\text{ Hg}\,(l) + 2\text{ Cl-}\,(aq)$

b) What is the equilibrium constant for this reaction? (4 marks)

$$E^o = E^o\left(\text{Right side}\right) - E^o\left(\text{Left side}\right)$$

$$= 0.26808\text{ V} - \left(-0.44\text{ V}\right) = 0.708\text{ V}$$

$$\Delta G_m^o = -RT\ln K = -vFE^o$$

$$\ln K = \frac{vFE^o}{RT} = \frac{2\left(96485\text{ C mol}^{-1}\right)\left(0.708\text{ V}\right)}{\left(8.314\text{ J K}^{-1}\text{ mol}^{-1}\right)\left(298.15\text{ K}\right)} = 55.1$$

$$K = 8.64 \times 10^{23}$$

c) Calculate the cell potential. (3 marks)

$$E = E^o - \frac{RT}{vF}\ln Q$$

$$Q = a_{\text{Cl}^-}^2 a_{\text{Fe}^{2+}}$$

$$= \left(2 \times 0.0250\right)^2\left(0.0250\right) = 6.25 \times 10^{-5}$$

$$E = 0.708\text{ V} - \frac{\left(8.314\text{ J K}^{-1}\text{ mol}^{-1}\right)\left(298.15\text{ K}\right)}{2\left(96485\text{ C mol}^{-1}\right)}\ln 6.25 \times 10^{-5}$$

$$= 0.832\text{ V}$$

Question 7. Calcium bicarbonate decomposes at elevated temperatures according to the stoichiometric equation:

$$Ca(HCO_3)_2\,(s) \rightleftharpoons CaCO_3\,(s) + CO_2\,(g) + H_2O\,(g)$$

Pure calcium bicarbonate is put into a sealed vessel and the air is pumped out. When the vessel and its contents are heated to 500 K the total pressure is 0.290 bar.

a) Calculate *Kp*. (2 marks)

$$Kp = \left(\frac{p_{CO_2}}{p^o}\right)\left(\frac{p_{H_2O}}{p^o}\right) = \left(\tfrac{1}{2}0.290\right)\left(\tfrac{1}{2}0.290\right) = 0.0210$$

b) What will happen to the partial pressure of CO_2 if 0.120 bar of H_2O gas is added to this equilibrium mixture, and the system is allowed to come to equilibrium again? Justify your answer with one sentence. (2 marks)

The partial pressure of CO_2 will decrease. The equilibrium will shift towards the reactants according to Le Châtelier's principle (since the equilibrium constant does not change).

c) If the air was not pumped out of the reaction vessel before heating the reaction, how would this affect *Kp*? Briefly explain your answer. (2 marks)

It would not affect *Kp*. *Kp* is a constant, and only changes with temperature, not pressure. Inert gases do not participate in the equilibrium.

d) Calculate the temperature that will increase the final pressure of the system by 2-fold. Assume that the enthalpy of the reaction (32.8 kJ/mol) is temperature independent. (3 marks)

The new total pressure is 2 x 0.290 bar, and therefore $p_{CO2} = p_{H2O} = 0.290$ bar.

$$Kp = \left(\frac{p_{CO_2}}{p^o}\right)\left(\frac{p_{H_2O}}{p^o}\right) = (0.290)(0.290) = 0.0841$$

$$\ln\left(\frac{K_2}{K_1}\right) = -\frac{\Delta H}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$\frac{1}{T_2} = -\frac{R}{\Delta H}\ln\left(\frac{K_2}{K_1}\right) + \frac{1}{T_1}$$

$$= -\frac{8.314\ \text{J K}^{-1}\ \text{mol}^{-1}}{32800\ \text{J mol}^{-1}}\ln\left(\frac{0.0841}{0.0210}\right) + \frac{1}{500\ \text{K}}$$

$$= 0061648\ \text{K}^{-1}$$

$$T_2 = 607\ \text{K}$$

Question 8. Suppose a sample of liquid water at 273.15 K is put into a freezer at -20.0°C.

a) What is the entropy change for 2.50 mol of water? (5 marks)

$$\begin{aligned}\Delta S &= \Delta S_{trs} + \Delta S_{\Delta T}\\ &= n\left[\frac{-\Delta H^o_{fus}}{T_{fus}} + C^o_{p,m}\ln\left(\frac{T_2}{T_1}\right)\right]\\ &= \left(2.50\text{ mol}\right)\left[\frac{-6010\text{ J mol}^{-1}}{273.15\text{ K}} + \left(36.2\text{ J K}^{-1}\text{ mol}^{-1}\right)\ln\left(\frac{253\text{ K}}{273\text{ K}}\right)\right]\\ &= -61.9\text{ J K}^{-1}\end{aligned}$$

$$\begin{aligned}\Delta H^o_{fus} + \Delta H^o_{vap} &= \Delta H^o_{sub}\\ \Delta H^o_{fus} &= \Delta H^o_{sub} - \Delta H^o_{vap}\\ &= 46.66\text{ kJ mol}^{-1} - 40.65\text{ kJ mol}^{-1}\\ &= 6.01\text{ kJ mol}^{-1}\end{aligned}$$

b) Is the freezing of water spontaneous in this situation? Provide support for your answer with a calculation. (6 marks)

$$\begin{aligned}\Delta S_{surr} &= \frac{-q_{sys}}{T_{surr}}\\ &= n\left[\frac{\Delta H^o_{fus} - C^o_{p,m}\Delta T}{T_{surr}}\right]\\ &= \left(2.50\text{ mol}\right)\left[\frac{-6010\text{ J mol}^{-1} - \left(36.2\text{ J K}^{-1}\text{ mol}^{-1}\right)\left(253\text{ K} - 273\text{ K}\right)}{253.15\text{ K}}\right]\\ &= 66.5\text{ J K}^{-1}\\ \Delta S_{surr} &= \Delta S_{sys} + \Delta S_{surr}\\ &= \left(-61.9 + 66.5\right)\text{J K}^{-1}\\ &= 4.6\text{ J K}^{-1}\end{aligned}$$

Since $\Delta S_{sys} > 0$, therefore the process will be spontaneous.

Question 9.

a) Assuming ideal behaviour, what is the solubility of $Ca(OH)_2$, (K_{sp}=6.50 x 10^{-6})? (2 marks)

$$K_{sp} = a_{\text{Ca}} a_{\text{OH}}^2 = s\left(2s\right)^2 = 4s^3$$

$$s = \sqrt[3]{\tfrac{1}{4}\left(6.50\times10^{-6}\right)} = 0.0118 \text{ mol kg}^{-1}$$

b) Calculate the mean activity coefficient for a saturated $Ca(OH)_2$ solution using the solubility calculated in a). (4 marks)

$$\begin{aligned}\log\gamma_{\pm} &= -\,|\,z+z-\,|\,0.5092\sqrt{I}\\ &= -\,|\,2\times-1\,|\,0.5092\sqrt{0.0354}\\ &= -0.192\\ \gamma_{\pm} &= 0.643\end{aligned}$$

$$\begin{aligned}I &= \tfrac{1}{2}\left[2^2\left(0.0118\right)+\left(-1\right)^2\left(2\times0.0118\right)^2\right]\\ &= 0.0354\end{aligned}$$

Question 10.

The dissolution of 7.75 g of a substance in 825 g of benzene at 298 K raises the boiling point by 0.575°C (K_b = 2.53 K kg mol^{-1}, density of benzene is 876.6 kg/m^3). What is the osmotic pressure of this solution? (5 marks)

$$\Delta T = K_b m = K_b \frac{n_{\text{substance}}}{m_{\text{benzene}}}$$

$$n_{\text{substance}} = \frac{\Delta T m_{\text{benzene}}}{K_b}$$

$$\text{density} = \frac{m}{V}$$

$$V = \frac{m}{\text{density}}$$

$$\begin{aligned}\pi &= \frac{n_{\text{substance}}}{V_{\text{benzene}}} RT\\ &= \frac{\Delta T m_{\text{benzene}}}{K_b V_{\text{benzene}}} RT\\ &= \frac{\Delta T m_{\text{benzene}}}{K_b \dfrac{m_{\text{benzene}}}{\text{density}_{\text{benzene}}}} RT\\ &= \frac{\left(0.575\text{ K}\right)\left(875\text{ g}\right)\left(8.314\text{ J K}^{-1}\text{ mol}^{-1}\right)\left(298\text{K}\right)}{\left(2.53\text{ K kg mol}^{-1}\right)\dfrac{825\text{ g}}{876.6\text{ g m}^3}}\\ &= 4.9\times10^5\text{ Pa} = 4.9\text{ bar} = 4.8\text{ atm}\end{aligned}$$

Question 11.

Calculate the standard entropy at 870 K for the dissociation of bromine: $B_2(g)$ -> 2 Br (g) given that: (6 marks)

$$\frac{C_{p,m}\left(\mathrm{Br}_2\right)}{\mathrm{J\ K^{-1}\ mol^{-1}}} = 36.05 + 30.11\ \frac{\mathrm{T}}{K}$$

$C_{p,m}(\mathrm{Br}) = 20.79\ \mathrm{J\ K^{-1}\ mol^{-1}}$

$$\Delta S_r^o\left(298\ \mathrm{K}\right) + 2\Delta S_{\Delta T}\left(Br\right) = \Delta S_{\Delta T}\left(Br_2\right) + \Delta S_r^o\left(870\ \mathrm{K}\right)$$

$$\Delta S_r^o\left(870\ \mathrm{K}\right) = \Delta S_r^o\left(298\ \mathrm{K}\right) + 2\Delta S_{\Delta T}\left(Br\right) - \Delta S_{\Delta T}\left(Br_2\right)$$

$$\Delta S_r^o\left(298\ \mathrm{K}\right) = 2S_m^o\left(\mathrm{Br}\right) - S_m^o\left(\mathrm{Br}_2\right) = \left[2\left(175.0\right) - 245.5\right]\ \mathrm{J\ K^{-1}\ mol^{-1}} = 104.5\ \mathrm{J\ K^{-1}\ mol^{-1}}$$

$$\Delta S_{\Delta T}\left(\mathrm{Br}\right) = \int_{T_1}^{T_2} \frac{C_{p,m}^o\left(\mathrm{Br}\right)}{T}dT = \int_{T_1}^{T_2} \frac{\left(20.70\ \mathrm{J\ K^{-1}\ mol^{-1}}\right)}{T}dT = \left(20.70\ \mathrm{J\ K^{-1}\ mol^{-1}}\right)\ln\left(\frac{T_2}{T_1}\right)$$

$$= \left(20.70\ \mathrm{J\ K^{-1}\ mol^{-1}}\right)\ln\left(\frac{870\ \mathrm{K}}{298\ \mathrm{K}}\right) = 22.178\ \mathrm{J\ K^{-1}\ mol^{-1}}$$

$$\Delta S_{\Delta T}\left(\mathrm{Br}_2\right) = \int_{T_1}^{T_2} \frac{C_{p,m}^o\left(\mathrm{Br}_2\right)}{T}dT = \int_{T_1}^{T_2} \frac{\left(36.05\ \mathrm{J\ K^{-1}\ mol^{-1}}\right) + \left(30.11\ \mathrm{J\ mol^{-1}}\right)T}{T}dT$$

$$= \left(36.05\ \mathrm{J\ K^{-1}\ mol^{-1}}\right)\ln\left(\frac{T_2}{T_1}\right) + \left(30.11\ \mathrm{J\ mol^{-1}}\right)\Delta T$$

$$= \left(36.05\ \mathrm{J\ K^{-1}\ mol^{-1}}\right)\ln\left(\frac{870\ \mathrm{K}}{298\ \mathrm{K}}\right) + \left(30.11\ \mathrm{J\ mol^{-1}}\right)\left(870\ \mathrm{K} - 298\ \mathrm{K}\right)$$

$$= 17261.5\ \mathrm{J\ K^{-1}\ mol^{-1}}$$

$$\Delta S_r^o\left(870\ \mathrm{K}\right) = \Delta S_r^o\left(298\ \mathrm{K}\right) + 2\Delta S_{\Delta T}\left(Br\right) - \Delta S_{\Delta T}\left(Br_2\right)$$

$$= \left[104.5 + 2\left(22.178\right) - 17261.5\right]\ \mathrm{J\ K^{-1}\ mol^{-1}}$$

$$= -17.1\ \mathrm{kJ\ K^{-1}\ mol^{-1}}$$

Constants and Conversion Factors

R = 8.314 J K^{-1} mol^{-1} = 0.08206 L atm mol^{-1} K^{-1} = 0.08314 L bar mol^{-1} K^{-1}

F = 96485 C mol^{-1} $N_A = 6.022 \times 10^{23}$ mol^{-1} e- = 1.6022 x 10^{-19} C

1 L = 1 dm^3 = 10^{-3} m^3 1 kJ = 1000 J 1 atm = 101325 Pa 760 Torr = 1 atm

1 bar = 10^5 Pa 1 L atm = 101.325 J 1 J = 1 kg m^2 s^{-2} 1 Pa = 1 kg m^{-1} s^{-2}

1 C s^{-1} = 1 amp

Data for H_2O

ΔH^o_{vap} = 40.65 kJ mol^{-1} ΔH^o_{sub} = 46.66 kJ/mol T_{vap} = 373.15 K T_{fus} = 273.15 K

$T_{triple\ point}$ = 273.16 K $p_{triple\ point}$ = 611 Pa M = 18.01 g mol^{-1} $m^*_{H_2O}$ = 55.555 mol kg^{-1}

ρ_{ice} = 920 kg m^{-3} $\rho_{liquid\ water}$ = 997 kg m^{-3} $p^*_{H_2O}$ = 3200 Pa at 298 K

Standard Reduction Potentials

$Fe^{2+} + 2\,e^- \rightarrow Fe$	-0.44 V
$Fe^{3+} + 3\,e^- \rightarrow Fe$	-0.04 V
$Hg_2^{2+} + 2\,e^- \rightarrow 2\,Hg$	+0.7973 V
$Hg^{2+} + 2\,e^- \rightarrow Hg$	+0.851 V
$Hg_2Cl_2 + 2\,e^- \rightarrow 2\,Hg + 2\,Cl^-$	+0.26808 V
$Hg_2SO_4 + 2\,e^- \rightarrow 2\,Hg + SO_4^{2-}$	+0.62 V

Thermodynamic Data at 298.15 K

Substance	$\Delta H^o_f\left(\text{kJ mol}^{-1}\right)$	$S^o_m\left(\text{J K}^{-1}\ \text{mol}^{-1}\right)$	$C^o_{p,m}\left(\text{J K}^{-1}\ \text{mol}^{-1}\right)$
Br_2 (g)	30.9	245.5	36.0
Br (g)	111.9	175.0	20.79
Ca^{2+} (aq)	-542.8	-53.1	99.7
$CaCO_3$ (s)	-1206.9	92.9	83.5
C (s, graphite)	0	5.74	8.52
C_6H_6O (s)	-165.1	144.0	127.4
CO_2 (g)	-393.5	213.8	37.1
H_2 (g)	0	130.7	28.8
H_2O (g)	-241.8	188.8	33.6
H_2O (l)	-285.8	70.0	75.3
H_2O (s)	--	48.0	36.2
O_2 (g)	0	205.2	29.4
OH- (aq)	-230.0	-10.9	--

$$pV = nRT$$

$$p = \frac{nRT}{V - nb} - a\left(\frac{n}{V}\right)^2$$

$$\Delta U = w + q$$

$$w = \int_{x_1}^{x_2} F \cdot dx$$

$$w = \int_{0}^{Q} \phi \cdot dQ'$$

$$w = -\int_{V_1}^{V_2} p_{ext}\, dV$$

$$C_p - C_V = nR$$

$$\Delta U = \int_{T_1}^{T_2} C_V\, dT$$

$$\Delta H = \int_{T_1}^{T_2} C_p\, dT$$

$$H = U + pV$$

$$\pi_T = \left(\frac{\partial U}{\partial V}\right)_T$$

$$\Delta S = \int \frac{\delta q_{rev}}{T}$$

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma} \quad \gamma = \frac{C_p}{C_V}$$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{(\gamma - 1)}$$

$$\Delta H_r^{\circ} = \sum_{\text{Products}} \nu \Delta H_f^{\circ} - \sum_{\text{Reactants}} \nu \Delta H_f^{\circ}$$

$$\varepsilon = \frac{T_{high} - T_{low}}{T_{high}}$$

$$\varepsilon = \frac{\left|\oint \delta w_{rev}\right|}{q_{AB}}$$

$$\Delta H_{r,T}^{\circ} = \Delta H_{r,298.15\,\text{K}}^{\circ} + \int_{T_1}^{T_2} \Delta C_p\left(T'\right) dT'$$

$$\Delta C_p\left(T'\right) = \sum_i \nu_i C_{p,i}\left(T'\right)$$

$$\Delta S = \int \frac{C_V}{T} dT$$

$$\Delta S = \int \frac{C_p}{T} dT$$

$$\Delta S = nR \ln \frac{V_f}{V_i}$$

$$\Delta_r S_m^{\circ} = \sum_{\text{Products}} \nu S_m^{\circ} - \sum_{\text{Reactants}} \nu S_m^{\circ}$$

$$\Delta S_{\text{Total}} = \Delta S_{\text{System}} + \Delta S_{\text{Surroundings}}$$

$$\Delta S_{\text{surr}} = \frac{-q_{\text{sys}}}{T_{\text{surr}}}$$

$$\Delta_{trs} S^o = \frac{\Delta_{trs} H^o}{T_{trs}}$$

$$\left(\frac{\partial G}{\partial p}\right)_T = V$$

$$\left(\frac{\partial G}{\partial T}\right)_p = -S$$

$$A = U - TS$$

$$G = H - TS$$

$$\Delta G = V \Delta p$$

$$\Delta\left(\Delta G\right) = \Delta V \Delta p$$

$$\Delta G_r^{\circ} = \sum_{\text{Products}} \nu \Delta G_f^{\circ} - \sum_{\text{Reactants}} \nu \Delta G_f^{\circ}$$

$$\Delta G = nRT \ln\left(\frac{p_2}{p_1}\right)$$

$$p_{\text{A}} = x_{\text{A}} p_{\text{T}}$$

$$x_{\text{A}} = \frac{n_{\text{A}}}{n_{\text{Total}}}$$

$$\Delta G\left(p_2\right) = \Delta G^o + nRT \ln\left(\frac{p_2}{p^o}\right)$$

$$\Delta G^{\text{mixing}} = RT \sum_i n_i \ln x_i = nRT \sum_i x_i \ln x_i$$

$$\Delta G_m^o = -RT \ln K$$

$$\ln\left(\frac{K_2}{K_1}\right) = -\frac{\Delta_r H_m}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$\frac{\Delta G\left(T_2\right)}{T_2} = \frac{\Delta G\left(T_1\right)}{T_1} + \Delta H\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$K_p = \prod_i \left(\frac{p_i}{p^o}\right)^{\nu_i}$$

$$K_p = \left(\frac{p_T}{p^o}\right)^{\Delta \nu_i} \prod_i x_i^{\nu_i} = \left(\frac{p_T}{p^o}\right)^{\Delta \nu_i} K_x$$

$$K = \left(\frac{c^o RT}{p^o}\right)^{\Delta \nu_i} \prod_i \left(\frac{c_i}{c^o}\right)^{\nu_i} = \left(\frac{c^o RT}{p^o}\right)^{\Delta \nu_i} K_c$$

$$\ln\left(\frac{p_2}{p_1}\right) = -\frac{\Delta_{trs} H_m}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$\frac{dp}{dT} = \frac{\Delta_{trs} H_m}{T_{trs} \Delta V_m}$$

$$m_{\text{A}} = K_{\text{A}} p_{\text{A}}$$

$$p_i = \chi_i p_i^*$$

$$y_A = \frac{p_A^* p_T - p_A^* p_B^*}{p_T\left(p_A^* - p_B^*\right)}$$

$$F = C - p + 2$$

$$p_{\text{A}} = \chi_{\text{A}} k_A^H$$

$$\frac{n_l^{Total}}{n_v^{Total}} = \frac{\left(y_A - Z_A\right)}{\left(Z_A - x_A\right)}$$

$$\mu_i = \mu_i^* + RT \ln\left(a_i\right)$$

$$a_i = \frac{p_i}{p_i^*}$$

$$a_i = \gamma_i \chi_i$$

$$\mu_i = \mu_i^o + RT \ln\left(a_i\right)$$

$$a_i = \gamma_i \frac{m_i}{m^o}$$

$$K_f = \frac{(MW) RT_f^{*2}}{\Delta_{fus} H}$$

$$\Delta T_f = K_f \times m_{solute}$$

$$\Delta T_b = K_b \times m_{solute}$$

$$\Pi = \left[B\right] RT$$

$$I = \frac{1}{2} \sum_i z_i^2 \frac{m_i}{m^o}$$

$$\log \gamma_{\pm} = -\left|z_+ z_-\right| \left(0.5092\right) \sqrt{I}$$

$$\int x^n\, dx = \frac{1}{n+1} x^{n+1} + c$$

$$\int \frac{dx}{x} = \ln x + c$$

$$\frac{dx^n}{dx} = \frac{1}{n} x^{n-1}$$

$$\Delta G_m = \Delta G_m^o + RT \ln Q$$

$$Q = \prod_i a_i^{vi}$$

$$E^o = E^o\left(\text{right}\right) - E^o\left(\text{left}\right)$$

$$\Delta G_m = -\nu FE$$

$$E = E^o - \frac{RT}{\nu F} \ln Q$$