04-CHEM-A1, PROCESS BALANCES and CHEMICAL THERMODYNAMICS

MAY 2016

Three Hours Duration

NOTES:

1) If doubt exists as to the interpretation of any question, you are urged to submit a clear statement of any assumptions made along with the answer paper.
2) Property data required to solve a given problem are provided in the problem statement or are available in the recommended texts. If you are unable to locate the required data, do not let this prevent you from solving the rest of the problem. Even in the absence of property data, you still have the opportunity to provide a solution methodology.
3) This is an open-book exam.
4) Any non-communicating calculator is permitted.
5) The examination is in two parts – Part A (Questions 1 to 3): Process Balances
   Part B (Questions 4 and 6): Chemical Thermodynamics
6) Answer **TWO** questions from Part A and **TWO** questions from Part B.
7) **FOUR** questions constitute a complete paper.
8) Each question is of equal value.

PART A: PROCESS MASS and ENERGY BALANCES

1) Consider an iron blast furnace charged with iron ore, limestone ($CaCO_3$) and coke. The weight analyses of the charge is as follows:

	Fe_2O_3	SiO_2	MnO	Al_2O_3	H_2O	C	$CaCO_3$
Ore	80%	12%	1%	3%	4%		
Limestone		4%			1%		95%
Coke		10%				90%	

The ultimate weight analysis of the pig iron gives 93.8% Fe, 4% C, 1.2% Si and 1% Mn. For every ton of pig iron produced, 1750 kg of iron ore and 500 kg of limestone are used and 4200 m^3 of flue gas is produced. The rational analysis of flue gases gives 58% N_2, 26% CO, 12% CO_2, and 4% H_2O. The reactions occurring in the blast furnace are:

$$Fe_2O_3 + 3CO \leftrightarrow 2Fe + 3CO_2$$

$$CaCO_3 \leftrightarrow CaO + CO_2$$

$$C + \tfrac{1}{2} O_2 \leftrightarrow CO$$

$$SiO_2 + 2C \leftrightarrow Si + 2CO$$

$$MnO + C \leftrightarrow Mn + CO_2$$

$$CO_2 + C \leftrightarrow 2CO$$

Determine the following:

a) Quantity of coke used per ton of pig iron
b) Consumption of air per ton of pig iron
c) Composition of the slag

2) Consider the oxidation of toluene given by the following reaction

$$C_6H_5CH_3\ (g) + O_2\ (g) \rightarrow C_6H_5CHO\ (g) + H_2O\ (g)$$

Calculate the standard heat of reaction for oxidation of toluene.

<u>DATA</u>:
Gross heat of combustion of liquid benzaldehyde at 18 °C = – 841.3 kcal/gmol
Normal boiling point of benzaldehyde = 179 °C
Heat of vaporization of benzaldehyde at 179 °C = 86.48 cal/g
Specific heat capacity of liquid benzaldehyde = 0.428 cal/g °C
Specific heat capacity of benzaldehyde vapor = 31 cal/gmol °C
Average molar heat capacity of liquid H_2O = 18 cal/gmol °C
Average molar heat capacity of CO_2 = 8.87 cal/gmol °C
Average molar heat capacity of O_2 = 7.0 cal/gmol °C
Standard heat of formation of H_2O vapor = – 57.8 kcal/gmol
Standard heat of formation of toluene vapor = 11.95 kcal/gmol

3) 1000 kg/hr of a liquid solution of 60 wt% naphthalene ($C_{10}H_8$) and 40 wt% benzene (C_6H_6) at 80 °C is cooled to 10 °C. The resulting solid and liquid phases are separated in a rotary drum filter. The process operates at steady state. Your job is to determine how well the drum filter is performing. You determine that the filtrate liquid flow rate is 505 kg/hr.

(a) How much entrainment (kg entrained/kg solids) does the filter leave?
(b) By how much does any entrainment change the recovery of naphthalene in the filter cake product or the purity of the products?

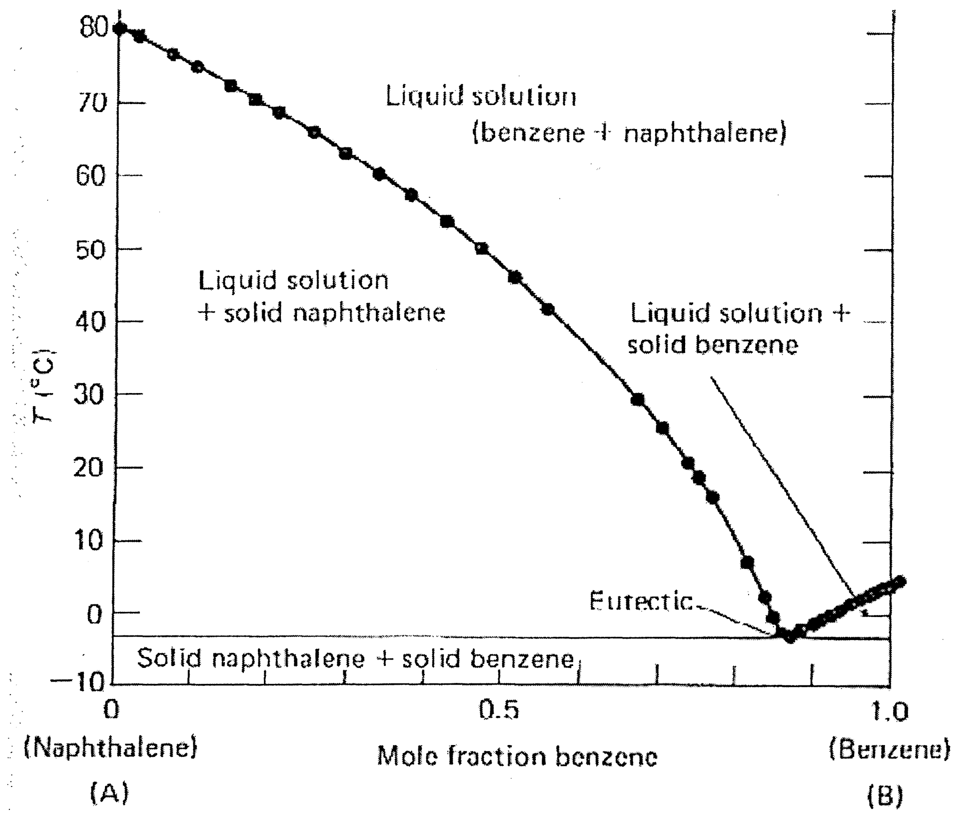

Figure: Liquid-Solid Phase Equilibrium Diagram for Benzene-Naphthalene Mixtures (taken from *"Phase Equilibria in Chemical Engineering"* by Stanley M. Walas, Butterworth Publishers, 1985)

PART B: CHEMICAL THERMODYNAMICS

4) The calcination of sodium bicarbonate takes place according to the following equation:

$$2NaHCO_3\ (s) \leftrightarrow Na_2CO_3\ (s) + CO_2\ (g) + H_2O\ (g)$$

When this reaction was run in the laboratory by placing sodium bicarbonate in an initially evacuated cylinder, it was observed that the equilibrium total pressure was 0.826 kPa at 30 ^{o}C and 166.97 kPa at 110 ^{o}C. The heat of reaction for the calcination can be assumed to be independent of temperature.

(a) What is the heat of reaction for this reaction?
(b) Develop an equation for the equilibrium constant as a function of temperature.
(c) At what temperature will the partial pressure of carbon dioxide in the reaction vessel be 1 bar?

5) At 45 ^{o}C and 40.25 kPa total pressure, a vapor phase containing 43.4 mol% ethanol and 56.6 mol% benzene is in equilibrium with a liquid phase containing 61.1 mol% benzene. The system forms an azeotrope at 45 ^{o}C. Assuming that few molecular interactions exist, determine the composition of the azeotrope and the total pressure of the azeotropic system.

DATA: Vapor pressure of pure ethanol at 45 ^{o}C = 22.9 kPa
Vapor pressure of pure ethanol at 45 ^{o}C = 29.6 kPa

6) A chemical species A is known to decompose according to the following equation:

$$A\ (g) \leftrightarrow B\ (g) + C\ (g)$$

A rigid container is filled with pure gaseous A at 300 K and 760 mmHg, and then heated. The pressure was observed to be 1114 mmHg at 400 K and 1584 mmHg at 500 K. Assuming ideal gas behavior and chemical equilibrium, estimate the pressure for a temperature of 600 K.

The Periodic Table of the Elements

- Alkali metals
- Alkaline earth metals
- Transition metals
- Other metals
- Metalloids (semi-metal)
- Nonmetals
- Halogens
- Noble gases

Element name → Mercury
Atomic # → 80
Symbol → Hg
Avg. Mass → 200.59

1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hydrogen 1 **H** 1.01																		Helium 2 **He** 4.00
Lithium 3 **Li** 6.94	Beryllium 4 **Be** 9.01												Boron 5 **B** 10.81	Carbon 6 **C** 12.01	Nitrogen 7 **N** 14.01	Oxygen 8 **O** 16.00	Fluorine 9 **F** 19.00	Neon 10 **Ne** 20.18
Sodium 11 **Na** 22.99	Magnesium 12 **Mg** 24.31												Aluminum 13 **Al** 26.98	Silicon 14 **Si** 28.09	Phosphorus 15 **P** 30.97	Sulfur 16 **S** 32.07	Chlorine 17 **Cl** 35.45	Argon 18 **Ar** 39.95
Potassium 19 **K** 39.10	Calcium 20 **Ca** 40.08		Scandium 21 **Sc** 44.96	Titanium 22 **Ti** 47.88	Vanadium 23 **V** 50.94	Chromium 24 **Cr** 52.00	Manganese 25 **Mn** 54.94	Iron 26 **Fe** 55.85	Cobalt 27 **Co** 58.93	Nickel 28 **Ni** 58.69	Copper 29 **Cu** 63.55	Zinc 30 **Zn** 65.39	Gallium 31 **Ga** 69.72	Germanium 32 **Ge** 72.61	Arsenic 33 **As** 74.92	Selenium 34 **Se** 78.96	Bromine 35 **Br** 79.90	Krypton 36 **Kr** 83.80
Rubidium 37 **Rb** 85.47	Strontium 38 **Sr** 87.62		Yttrium 39 **Y** 88.91	Zirconium 40 **Zr** 91.22	Niobium 41 **Nb** 92.91	Molybdenum 42 **Mo** 95.94	Technetium 43 **Tc** (98)	Ruthenium 44 **Ru** 101.07	Rhodium 45 **Rh** 102.91	Palladium 46 **Pd** 106.42	Silver 47 **Ag** 107.87	Cadmium 48 **Cd** 112.41	Indium 49 **In** 114.82	Tin 50 **Sn** 118.71	Antimony 51 **Sb** 121.76	Tellurium 52 **Te** 127.60	Iodine 53 **I** 126.90	Xenon 54 **Xe** 131.29
Cesium 55 **Cs** 132.91	Barium 56 **Ba** 137.33	57-70 *	Lutetium 71 **Lu** 174.97	Hafnium 72 **Hf** 178.49	Tantalum 73 **Ta** 180.95	Tungsten 74 **W** 183.84	Rhenium 75 **Re** 186.21	Osmium 76 **Os** 190.23	Iridium 77 **Ir** 192.22	Platinum 78 **Pt** 195.08	Gold 79 **Au** 196.97	Mercury 80 **Hg** 200.59	Thallium 81 **Tl** 204.38	Lead 82 **Pb** 207.20	Bismuth 83 **Bi** 208.98	Polonium 84 **Po** (209)	Astatine 85 **At** (210)	Radon 86 **Rn** (222)
Francium 87 **Fr** (223)	Radium 88 **Ra** (226)	89-102 **	Lawrencium 103 **Lr** (262)	Rutherfordium 104 **Rf** (267)	Dubnium 105 **Db** (268)	Seaborgium 106 **Sg** (271)	Bohrium 107 **Bh** (272)	Hassium 108 **Hs** (270)	Meitnerium 109 **Mt** (276)	Darmstadtium 110 **Ds** (281)	Roentgenium 111 **Rg** (280)	Copernicium 112 **Cn** (285)	Ununtrium 113 **Uut** (284)	Ununquadium 114 **Uuq** (289)	Ununpentium 115 **Uup** (288)	Ununhexium 116 **Uuh** (293)	Ununseptium 117 **Uus** (294?)	Ununoctium 118 **Uuo** (294)

*lanthanides	Lanthanum 57 **La** 138.91	Cerium 58 **Ce** 140.12	Praseodymium 59 **Pr** 140.91	Neodymium 60 **Nd** 144.24	Promethium 61 **Pm** (145)	Samarium 62 **Sm** 150.36	Europium 63 **Eu** 151.97	Gadolinium 64 **Gd** 157.25	Terbium 65 **Tb** 158.93	Dysprosium 66 **Dy** 162.50	Holmium 67 **Ho** 164.93	Erbium 68 **Er** 167.26	Thulium 69 **Tm** 168.93	Ytterbium 70 **Yb** 173.04
**actinides	Actinium 89 **Ac** (227)	Thorium 90 **Th** 232.04	Protactinium 91 **Pa** 231.04	Uranium 92 **U** 238.03	Neptunium 93 **Np** (237)	Plutonium 94 **Pu** (244)	Americium 95 **Am** (243)	Curium 96 **Cm** (247)	Berkelium 97 **Bk** (247)	Californium 98 **Cf** (251)	Einsteinium 99 **Es** (252)	Fermium 100 **Fm** (257)	Mendelevium 101 **Md** (258)	Nobelium 102 **No** (259)