16-CHEM-A1, PROCESS BALANCES and CHEMICAL THERMODYNAMICS

NATIONAL EXAMS DECEMBER 2018

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 (3 Questions): Process Balances
   Part B (3 Questions): 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 BALANCES

1) A liquid mixture containing containing 30% by mole benzene, 25% by mole toluene, and 45% by mole xylene is fed to a distillation column. The bottom product contains 98% by mole xylene and no benzene, and 96% of the xylene in the feed is recovered in this stream. The overhead product from the column is fed to a second distillation column. The overhead product from the second column contains 97% by mole benzene in the feed to this column. The composition of this stream is 94% by mole benzene and the rest toluene.

   (a) **[17 points]** Draw and label a simple flowchart of this process, and do a degree of freedom analysis to prove that for an assumed basis of calculation, molar flow rates and compositions of all process streams can be calculated from the given information. Write in order the equations you would solve to calculate unknown process variables. In each equation (or pair of simultaneous equations), circle the variable(s) for which you would solve. Do not perform any calculations.

   (b) **[4 points]** Calculate the percentage of benzene in the feed to the first distillation column that emerges in the overhead product from the second distillation column.

   (c) **[4 points]** Calculate the percentage of toluene in the feed to the first distillation column that emerges in the bottom product from the second distillation column.

2) Air of 97% relative humidity at 1 atm pressure and 311 K is to be cooled to 291 K, and fed into a plant at a rate of 8.5 m^3/s.

(a) [12 points] Calculate the rate in kg/min at which the water condenses.

(b) [13 points] Calculate the cooling requirement in tons assuming that the enthalpy of water vapor is that of saturated steam at the same temperature and the enthalpy of dry air (in kJ/mol) as a function of temperature (in °C) is given by the equation

$$H = 0.029\,(T - 25)$$

DATA: Saturation vapor pressure of water at 311 K = 6.54×10^{-2} atm
Saturation vapor pressure of water at 291 K = 2.04×10^{-2} atm
Enthalpy of saturated steam at 311 K = 2570.8 kJ/kg

Enthalpy of saturated steam at 291 K = 2534.5 kJ/kg

Enthalpy of liquid water at 291 K = 75.5 kJ/kg

One ton of cooling = 12,660 kJ/hr

3) Methanol (CH_3OH) is produced by reacting CO and H_2 according to the equation

$$CO + 2H_2 \rightarrow CH_3OH$$

Only 15% of the CO entering the reactor is converted to methanol. The methanol product is condensed and separated from the unreacted gases, which are recycled. The feed to the reactor contains 2 kmoles of H_2 for every kmole of CO. The fresh feed enters at 35 °C and 300 atm. To produce 6,600 kg/hr of methanol, calculate the following:

(a) [12 points] Volume of fresh feed gas.

(b) [13 points] Recycle ratio.

PART B: CHEMICAL THERMODYNAMICS

1) A gas obeys the following equation of state:

$$P\,(v - B) = RT + (AP^2/T)$$

where P is the pressure, v is the specific volume, T is the temperature, R is the universal gas constant, and A and B are constants for a gas.

(a) [17 points] Calculate the entropy change involved when the gas changes from 4 atm and 300 K to 12 atm and 400 K.

(b) [8 points] Estimate the mean specific heat (c_p) at 12 atm.

DATA:

Mean specific heat (c_p) at 1 atm = 8 cal/g
Value of constant A = 1 liter.K/atm.mol
Value of constant B = 0.08 liter/mol

2) A gaseous mixture contains the following three isomers of pentane (C_5H_{12}); n-pentane, isopentane and neopentane. The formation reaction of each of the isomer is listed below:

$$5C\ (s) + 6H_2\ (g) \leftrightarrow n\text{-}C_5H_{12}\ (g)$$

$$5C\ (s) + 6H_2\ (g) \leftrightarrow iso\text{-}C_5H_{12}\ (g)$$

$$5C\ (s) + 6H_2\ (g) \leftrightarrow neo\text{-}C_5H_{12}\ (g)$$

Calculate the equilibrium composition of the above gaseous mixture containing the three isomers at 400 K and 1 atm.

<u>DATA at 400 K</u>:

Standard Gibbs free energy of formation of n-pentane = $(\Delta G^o_f)_{\text{n-pentene}}$ = 40.195 kJ/mole
Standard Gibbs free energy of formation of iso-pentane = $(\Delta G^o_f)_{\text{iso-pentene}}$ = 34.415 kJ/mole
Standard Gibbs free energy of formation of neo-pentane = $(\Delta G^o_f)_{\text{neo-pentene}}$ = 37.640 kJ/mole

3) Hydrogen cyanide (HCN) can also be produced by gas-phase nitrogenation of acetylene (C_2H_2) according to the reaction

$$N_2\ (g) + C_2H_2\ (g) \leftrightarrow 2HCN\ (g)$$

The feed to the reactor consists of gaseous N_2 and C_2H_2 in their stoichiometric proportions and the reaction temperature is controlled at 573 K. Estimate the maximum mole fraction of HCN in the product stream for a reactor pressure of 200 bar. At this pressure, the assumption of ideal gas behavior is not valid. Instead, you can assume the gas mixture is an ideal solution.

DATA:

Critical temperature (T_c) of N_2 = 126.2 K

Critical pressure (P_c) of N_2 = 33.9 bar

Acentric factor (ω) of N_2 = 0.04

Critical temperature (T_c) of C_2H_2 = 308.3

Critical pressure (P_c) of C_2H_2 = 61.4 bar

Acentric factor (ω) of C_2H_2 = 0.184

Critical temperature (T_c) of HCN = 456.7 K

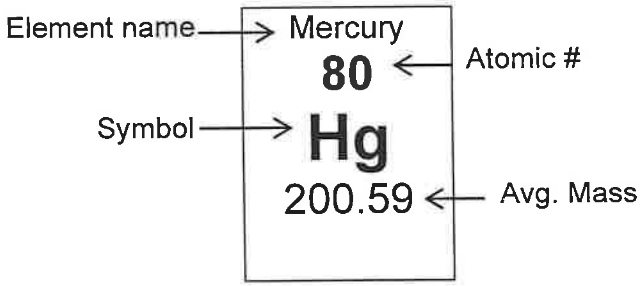
Critical pressure (P_c) of HCN = 49.6 bar

Acentric factor (ω) of HCN = 0.4

Standard Gibbs free energy of reaction at 573 K = $(\Delta G^o_{573})_{rxn}$ = 30.1 kJ/mole

The Periodic Table of the Elements

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



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)