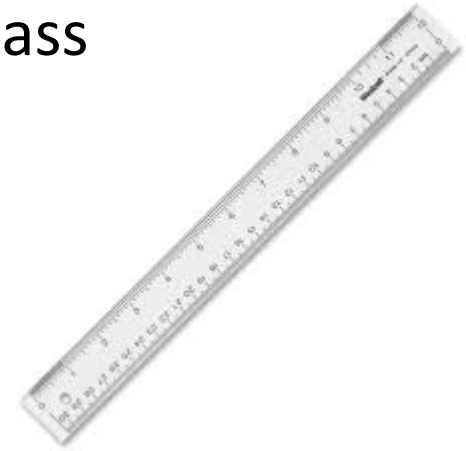
Exam 2
Ch. 5 thru Ch. 6

- Take Home
- Closed Book, Closed Notes
- One 8.5 x 11 paper with notes (one side)
- 3 hour time limit
- 7 problems
- Monday (today) through Friday
  - Due Friday morning at 9:00 am before class
- Needed:
  - Calculator
  - Ruler
  - Pencil



After the Exam

- 12 “lectures”
- 1 Exam Review
- 3rd Exam
- 5 class periods to work on Case Study
- Review for Final Exam

Get Some Help!
(We covered a lot of new concepts)

- TA sessions
- I will come to class on Wednesday
- Contact me!
  - I am relatively free
    - Mon afternoon
    - Most of Wed (except at noon)
    - Thursday most of the day
- PLEASE catch up on homework!
  - 50% credit until you take the exam
  - Use the answer key!

What Do I Study?
First Look at Competencies

- Students will understand process variables (e.g., P, T, flow rate, conc.) including procedures and equipment for their measurement.
- Students will be able to apply solution thermodynamics fundamentals to solve phase equilibrium problems including bubble point, dew point and flash calculations.
- Students will be able to read and understand phase diagrams and use these to determine physical phenomena.
- Students will understand pure-component, PVT phase behavior including vapor pressure, critical point, freezing line, triple point, etc.
- Students will understand how molecular interactions to the behavior of material gives rise to macroscopic properties.

F19 Exam
(Your Practice Exam)

1. Steam Tables	94%
2. Relative Humidity	88%
3. Ternary Phase Diagram	93%
4. Bubble Point Calculation	99%
5. Kay's Rule (non-ideal gas)	91%
6. Ideal Gas and VLE	83%

Average = 90%

Exam 2 Review Sheet

Chemical Engineering 273

1. **Single-Phase Systems**
   a. Liquid densities of mixtures
   b. Ideal gas
      i. Most common equation of state
      ii. Range of applicability (check $\tilde{V}_{ideal}$)
      iii. Mixtures (partial pressure, volume fraction, mole fraction)
   c. Standard temperature and pressure (SCF, SLPM, etc.)
   d. Non-ideal equations of state
      i. Van der Waals
      ii. SRK
      iii. Corresponding States ($P_r = P/P_c$, $T_r = T/T_c$) and compressibility factor (z)
      iv. Kay's rule for mixtures ($P_c' = \sum y_i P_{c,i}$, $T_c' = \sum y_i T_{c,i}$)
2. **Multiphase Systems**
   a. Single-component phase behavior
   b. Tables for Saturated Steam (B.3, B.5, B.6)
   c. Vapor pressure estimation (P_i^*) – Antoine, DIPPR, Fig. 6.1-4
   d. Gibbs phase rule
   e. Gas-liquid systems with one condensable component
      i. Raoult's Law ($y_i P_{tot} = x_i P_i^*$, but $x_i = 1$)
      ii. Humidity and drying (relative humidity, absolute humidity, degrees superheat)
   f. Multicomponent Systems
      i. Raoult's Law ($y_i P_{tot} = x_i P_i^*$)
         1. Assumptions
            a. Ideal systems
            b. Real systems where x_A is close to 1
         2. Dew point and bubble point
         3. 2 phase separation (Flash calculations)
         4. Non-condensable gas above liquid mixture (like air or N_2)
      ii. Henry's Law ($y_i P_{tot} = x_i H_i$, used for small x_i) (will not be on exam)
      iii. Diagrams
         1. Vapor-liquid diagrams (T-xy and P-xy)
         2. Solid-Liquid phase diagram
         3. Liquid-Liquid ternary diagram
         4. Tie lines and lever rule
      iv. Material balances using phase equilibrium data/calculations

- Look through the review sheet with a neighbor
- Identify what you would like to review most

Definition of Pressures

- P_{tot} Total Pressure, as in PV=znRT
- P_i Partial Pressure $P_i = y_i P_{tot}$
  $P_i V = z_i n_i RT$
- P_i^* Vapor Pressure = f(T),
  used in Raoult's law
- Raoult's Law

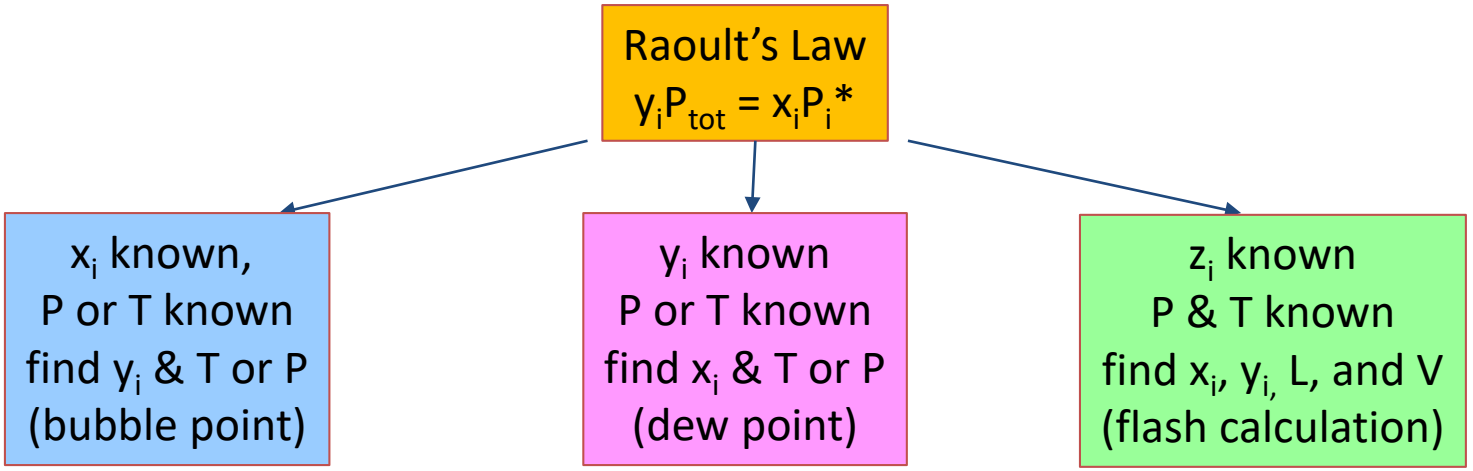
$$y_i P_{tot} = x_i P_i^*$$

Standard State Conditions

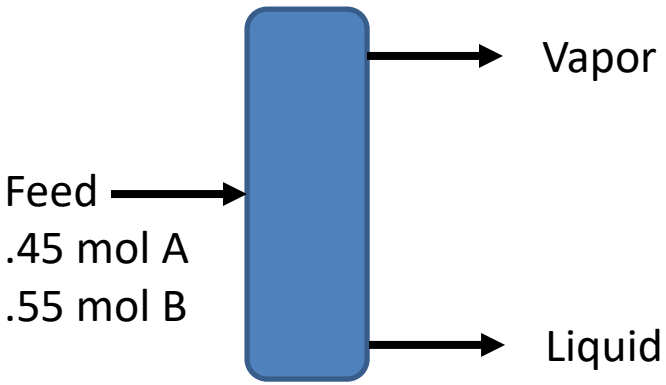
- Normally at 1 atm and 0°C
- Commonly used in measurements
- Concept: moles are the same
- $n = \left(\frac{PV}{RT}\right)_{STP} = \left(\frac{PV}{RT}\right)_{actual}$
- Example:

  Your flow meter says 30 slpm, and you measure T=30°C and P=5 psig. What is the actual volumetric flow rate?

Multicomponent Logic Chart



Flash Calculation Example



T = 50°C
P_{tot} = 700 mm Hg

Using T = 50°C
P_A^* = 600 mm Hg
P_B^* = 800 mm Hg

- Start with Raoult's Law

  $y_A P = x_A P_A^*$

  $y_B P = x_B P_B^*$

- Add the two equations

  $y_A P + y_B P = x_A P_A^* + x_B P_B^*$

- So

  $P = x_A P_A^* + (1-x_A) P_B^*$ to get x_A

- From x_A get x_B, y_A, y_B
- Mole Balances

  $n_F = n_L + n_V$

  $.45\, n_F = y_A\, n_V + x_A\, n_L$

  } Solve for n_V/n_F

Table B.3 Vapor Pressure of Water[a]

p_v(mm Hg) versus T(°C)
Example: The vapor pressure of liquid water at 4.3°C is 6.230 mm Hg

	T(°C)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
↓	−14	1.361	1.348	1.336	1.324	1.312	1.300	1.288	1.276	1.264	1.253
↓	−13	1.490	1.477	1.464	1.450	1.437	1.424	1.411	1.399	1.386	1.373
Ice	−12	1.632	1.617	1.602	1.588	1.574	1.559	1.546	1.532	1.518	1.504
	−11	1.785	1.769	1.753	1.737	1.722	1.707	1.691	1.676	1.661	1.646
	−10	1.950	1.934	1.916	1.899	1.883	1.866	1.849	1.833	1.817	1.800
	−9	2.131	2.122	2.093	2.075	2.057	2.039	2.021	2.003	1.985	1.968
	−8	2.326	2.306	2.285	2.266	2.246	2.226	2.207	2.187	2.168	2.149
	−7	2.537	2.515	2.493	2.472	2.450	2.429	2.408	2.387	2.367	2.346
	−6	2.765	2.742	2.718	2.695	2.672	2.649	2.626	2.603	2.581	2.559
	−5	3.013	2.987	2.962	2.937	2.912	2.887	2.862	2.838	2.813	2.790
	−4	3.280	3.252	3.225	3.198	3.171	3.144	3.117	3.091	3.065	3.039
	−3	3.568	3.539	3.509	3.480	3.451	3.422	3.393	3.364	3.336	3.308
	−2	3.880	3.848	3.816	3.785	3.753	3.722	3.691	3.660	3.630	3.599
	−1	4.217	4.182	4.147	4.113	4.079	4.045	4.012	3.979	3.946	3.913
	−0	4.579	4.542	4.504	4.467	4.431	4.395	4.359	4.323	4.287	4.252
↓	0	4.579	4.613	4.647	4.681	4.715	4.750	4.785	4.820	4.855	4.890
↓	1	4.926	4.962	4.998	5.034	5.070	5.107	5.144	5.181	5.219	5.256
Liquid	2	5.294	5.332	5.370	5.408	5.447	5.486	5.525	5.565	5.605	5.645
water	3	5.685	5.725	5.766	5.807	5.848	5.889	5.931	5.973	6.015	6.058
	4	6.101	6.144	6.187	6.230	6.274	6.318	6.363	6.408	6.453	6.498
	5	6.543	6.589	6.635	6.681	6.728	6.775	6.822	6.869	6.917	6.965
	6	7.013	7.062	7.111	7.160	7.209	7.259	7.309	7.360	7.411	7.462
	7	7.513	7.565	7.617	7.669	7.722	7.775	7.828	7.882	7.936	7.990
	8	8.045	8.100	8.155	8.211	8.267	8.323	8.380	8.437	8.494	8.551
	9	8.609	8.668	8.727	8.786	8.845	8.905	8.965	9.025	9.086	9.147
	10	9.209	9.271	9.333	9.395	9.458	9.521	9.585	9.649	9.714	9.779
	11	9.844	9.910	9.976	10.042	10.109	10.176	10.244	10.312	10.380	10.449
	12	10.518	10.588	10.658	10.728	10.799	10.870	10.941	11.013	11.085	11.158
	13	11.231	11.305	11.379	11.453	11.528	11.604	11.680	11.756	11.833	11.910
	14	11.987	12.065	12.144	12.223	12.302	12.382	12.462	12.543	12.624	12.706
	15	12.788	12.870	12.953	13.037	13.121	13.205	13.290	13.375	13.461	13.547
	16	13.634	13.721	13.809	13.898	13.987	14.076	14.166	14.256	14.347	14.438
	17	14.530	14.622	14.715	14.809	14.903	14.997	15.092	15.188	15.284	15.380
	18	15.477	15.575	15.673	15.772	15.871	15.971	16.771	16.171	16.272	16.374
	19	16.477	16.581	16.685	16.789	16.894	16.999	17.105	17.212	17.319	17.427
	20	17.535	17.644	17.753	17.863	17.974	18.085	18.197	18.309	18.422	18.536
	21	18.650	18.765	18.880	18.996	19.113	19.231	19.349	19.468	19.587	19.707
	22	19.827	19.948	20.070	20.193	20.316	20.440	20.565	20.690	20.815	20.941
	23	21.068	21.196	21.324	21.453	21.583	21.714	21.845	21.977	22.110	22.243
	24	22.377	22.512	22.648	22.785	22.922	23.060	23.198	23.337	23.476	23.616

[a]From R. H. Perry and C. H. Chilton, Eds., *Chemical Engineers' Handbook*, 5th Edition, McGraw-Hill, New York, 1973, Tables 3-3 and 3-5. Reprinted by permission of McGraw-Hill Book Co.

(*continued*)

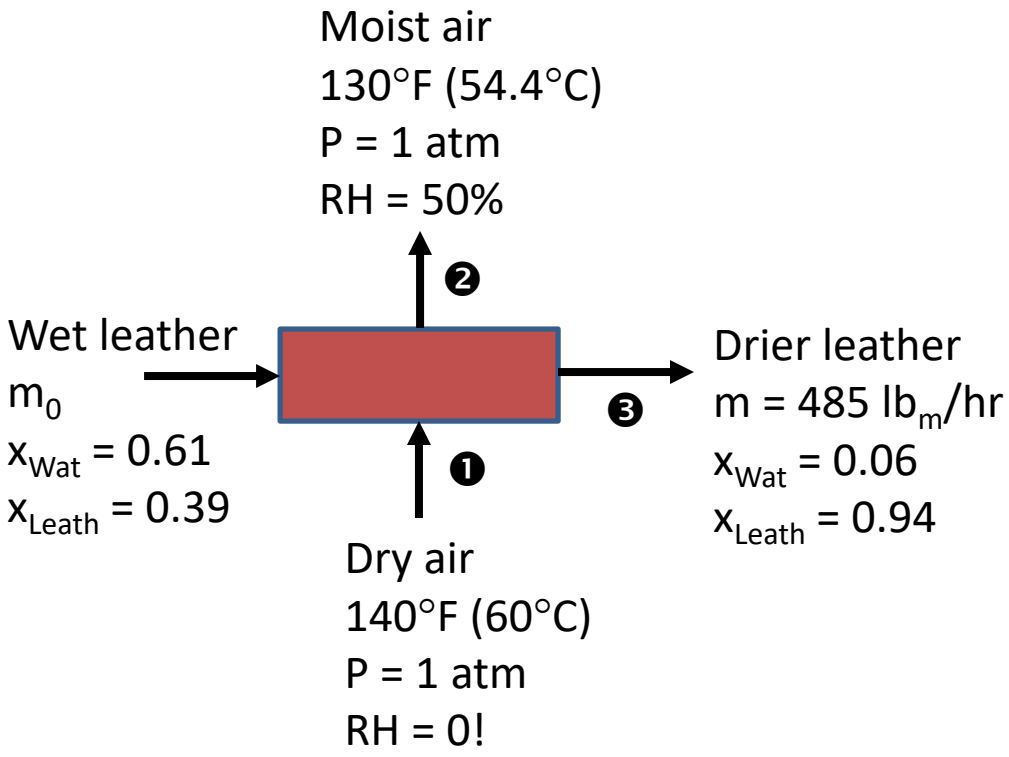
Table B.3 (Continued)

T(°C)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
25	23.756	23.897	24.039	24.182	24.326	24.471	24.617	24.764	24.912	25.060
26	25.209	25.359	25.509	25.660	25.812	25.964	26.117	26.271	26.426	26.582
27	26.739	26.897	27.055	27.214	27.374	27.535	27.696	27.858	28.021	28.185
28	28.349	28.514	28.680	28.847	29.015	29.184	29.354	29.525	29.697	29.870
29	30.043	30.217	30.392	30.568	30.745	30.923	31.102	31.281	31.461	31.642
30	31.824	32.007	32.191	32.376	32.561	32.747	32.934	33.122	33.312	33.503
31	33.695	33.888	34.082	34.276	34.471	34.667	34.864	35.062	35.261	35.462
32	35.663	35.865	36.068	36.272	36.477	36.683	36.891	37.099	37.308	37.518
33	37.729	37.942	38.155	38.369	33.584	38.801	38.018	39.237	39.457	39.677
34	39.898	40.121	40.344	40.569	40.796	41.023	41.251	41.480	41.710	41.942
35	42.175	42.409	42.644	42.880	43.117	43.355	43.595	43.836	44.078	44.320
36	44.563	44.808	45.054	45.301	45.549	45.799	46.050	46.302	46.556	46.811
37	47.067	47.324	47.582	47.841	48.102	48.364	48.627	48.891	49.157	49.424
38	49.692	49.961	50.231	50.502	50.774	51.048	51.323	51.600	51.879	52.160
39	52.442	52.725	53.009	53.294	53.580	53.867	54.156	54.446	54.737	55.030
40	55.324	55.61	55.91	56.21	56.51	56.81	57.11	57.41	57.72	58.03
41	58.34	58.65	58.96	59.27	59.58	59.90	60.22	60.54	60.86	61.18
42	61.50	61.82	62.14	62.47	62.80	63.13	63.46	63.79	64.12	64.46
43	64.80	65.14	65.48	65.82	66.16	66.51	66.86	67.21	67.56	67.91
44	68.26	68.61	68.97	69.33	69.69	70.05	70.41	70.77	71.14	71.51
45	71.88	72.25	72.62	72.99	73.36	73.74	74.12	74.50	74.88	75.26
46	75.65	76.04	76.43	76.82	77.21	77.60	78.00	78.40	78.80	79.20
47	79.60	80.00	80.41	80.82	81.23	81.64	82.05	82.46	82.87	83.29
48	83.71	84.13	84.56	84.99	85.42	85.85	86.28	86.71	87.14	87.58
49	88.02	88.46	88.90	89.34	89.79	90.24	90.69	91.14	91.59	92.05

T(°C)	0	1	2	3	4	5	6	7	8	9
50	92.51	97.20	102.09	107.20	112.51	118.04	123.80	129.82	136.08	142.60
60	149.38	156.43	163.77	171.38	179.31	187.54	196.09	204.96	214.17	223.73
70	233.7	243.9	254.6	265.7	277.2	289.1	301.4	314.1	327.3	341.0
80	355.1	369.7	384.9	400.6	416.8	433.6	450.9	468.7	487.1	506.1

T(°C)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
90	525.76	527.76	529.77	531.78	533.80	535.82	537.86	539.90	541.95	544.00
91	546.05	548.11	550.18	552.26	554.35	556.44	558.53	560.64	562.75	564.87
92	566.99	569.12	571.26	573.40	575.55	577.71	579.87	582.04	584.22	586.41
93	588.60	590.80	593.00	595.21	597.43	599.66	601.89	604.13	606.38	608.64
94	610.90	613.17	615.44	617.72	620.01	622.31	624.61	626.92	629.24	631.57
95	633.90	636.24	938.59	640.94	643.30	645.67	648.05	650.43	652.82	655.22
96	657.62	660.03	662.45	664.88	667.31	669.75	672.20	674.66	677.12	679.69
97	682.07	684.55	687.04	689.54	692.05	694.57	697.10	699.63	702.17	704.71
98	707.27	709.83	712.40	714.98	717.56	720.15	722.75	725.36	727.98	730.61
99	733.24	735.88	738.53	741.18	743.85	746.52	749.20	751.89	754.58	757.29
100	760.00	762.72	765.45	768.19	770.93	773.68	776.44	779.22	782.00	784.78
101	787.57	790.37	793.18	796.00	798.82	801.66	804.50	807.35	810.21	813.08

Humidity Problem Example
(Problem 6.34)



- Dry leather balance

  $0.39\ m_0 = 0.94 \times 485\ lb_m/hr$

- Find $y_{H2O,2}$

  $y_{H2O,2}\ P = RH \times P^*_{H2O}$

- Water balance

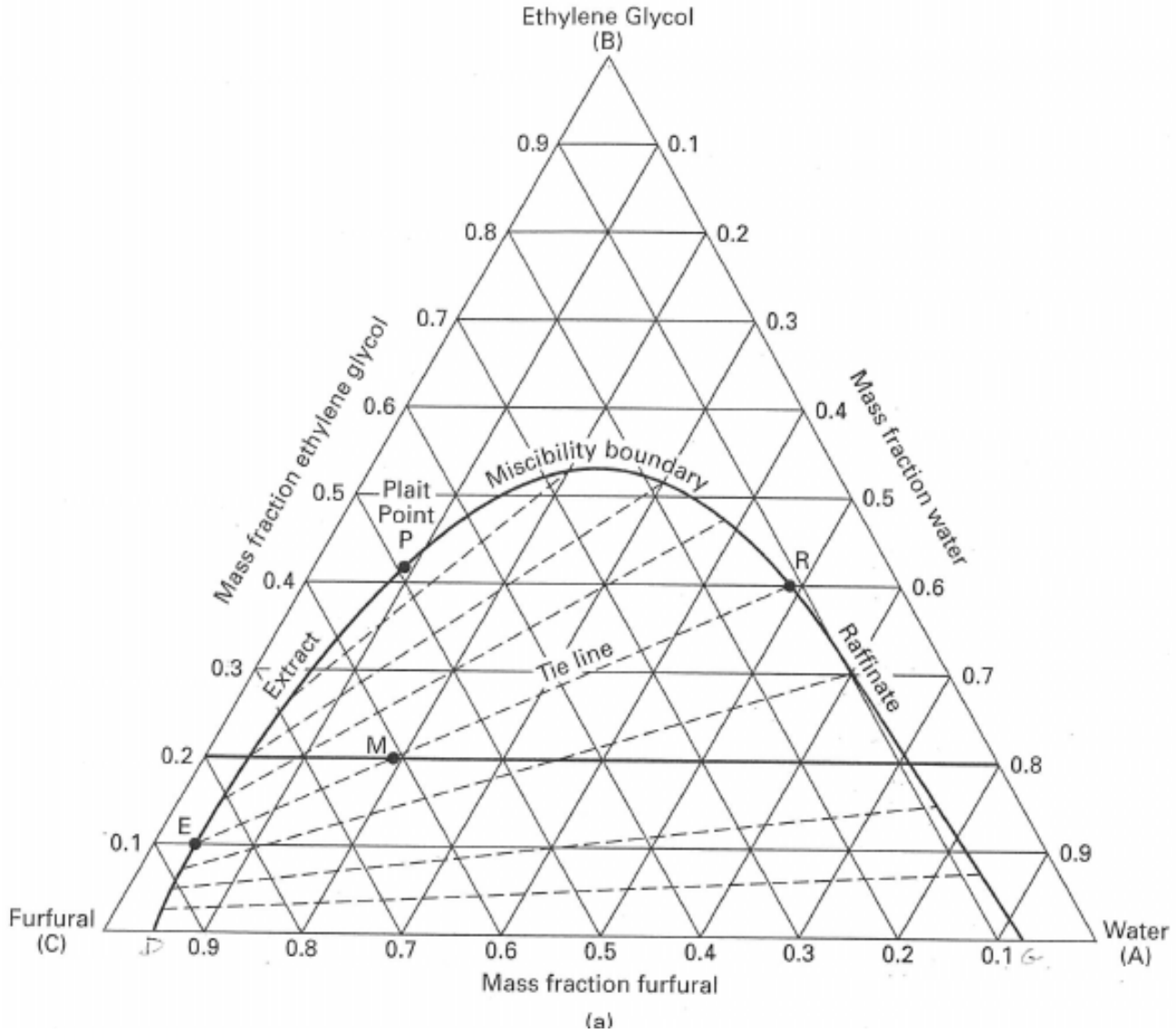
$0.61\ m_0 = y_{H2O,2}\ n_2\ (18\ lb/lbmol) + 0.06\ (485\ lb_m/hr)$
(solve for n_2)

- Dry air balance

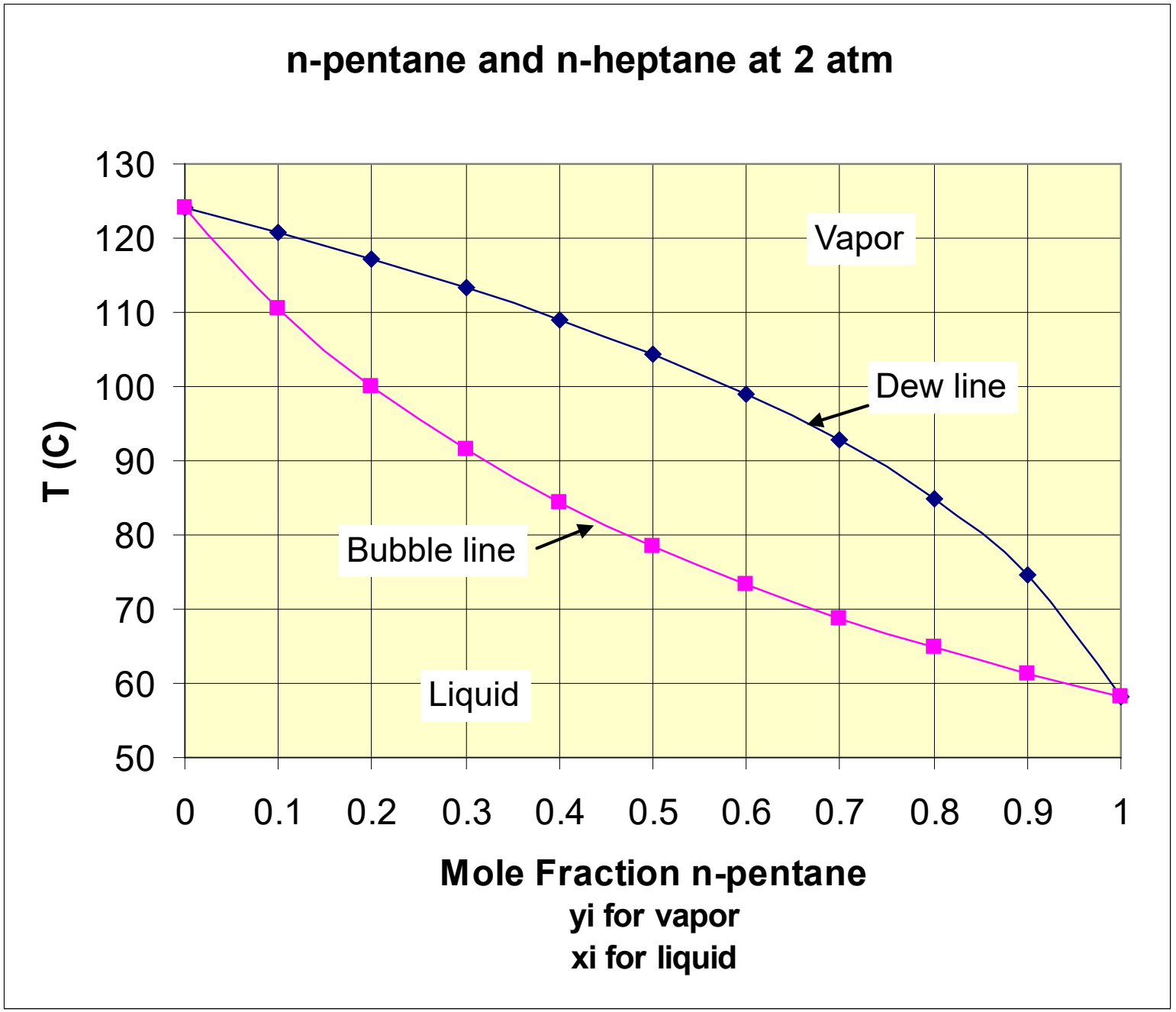
  $n_1 = (1 - y_{H2O,2})\ n_2$

  Then use $PV_1 = n_1RT$

Find:
(a) m_0 (inlet mass flow rate of wet leather)
(b) V_1 (volumetric flow of dry air)

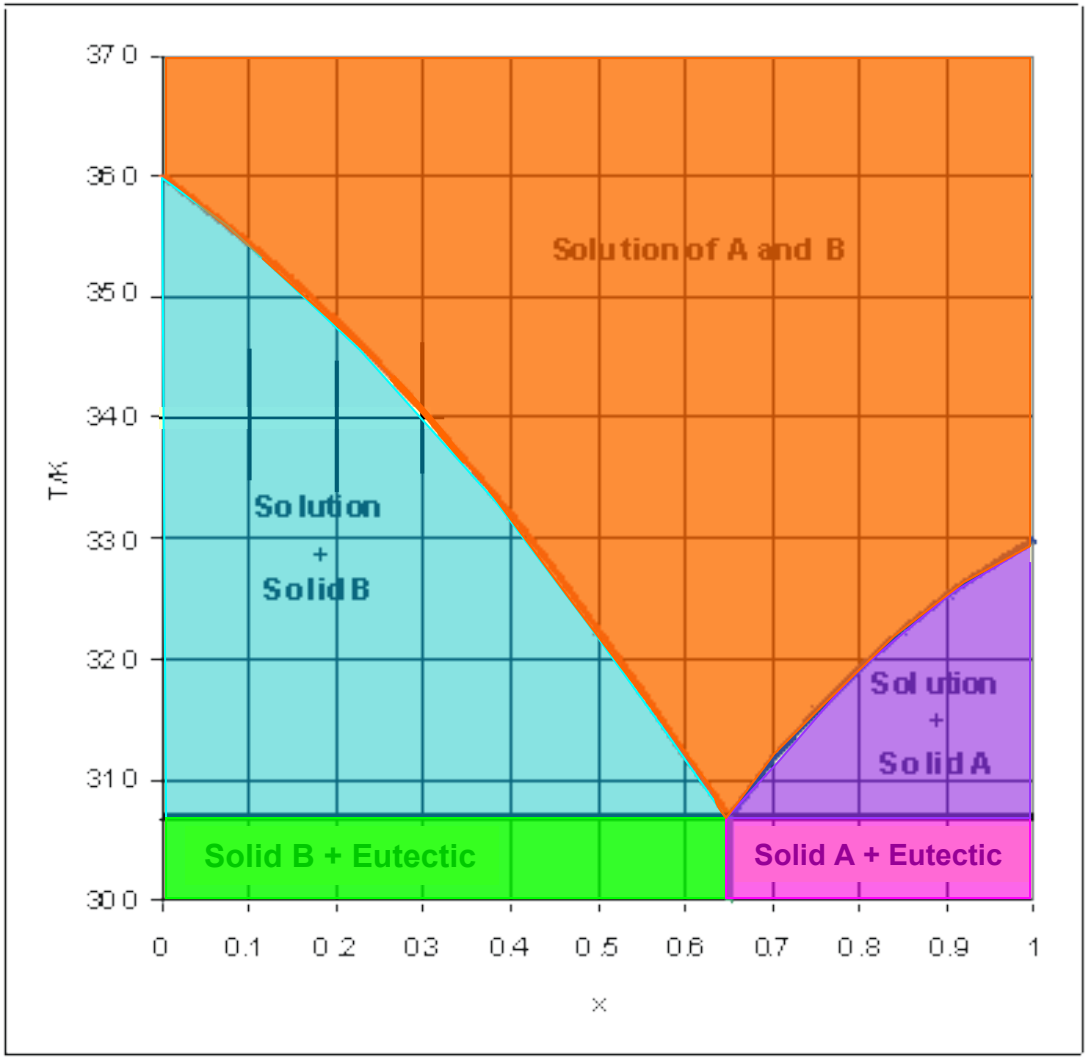

Ethylene Glycol
(B)
Furfural
(C)
Water
(A)
Mass fraction ethylene glycol
Mass fraction water
Mass fraction furfural
Miscibility boundary
Plait
Point
P
R
E
M
Extract
Raffinate
Tie line
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

(a)



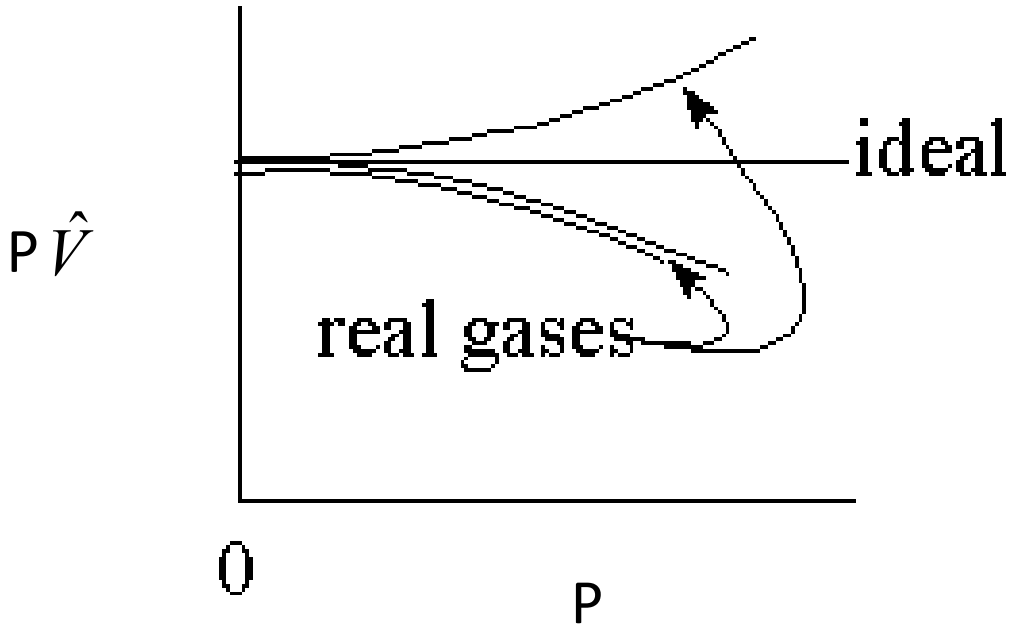
Generated from Raoult's law using the DIPPR vapor pressure correlations

Solid-Liquid Phase Diagrams



Mole fraction of A

Ideal vs. Real Gases



From p. 192, ideal when:

$$\hat{V}_{ideal} > 5L/mol \quad (diatomic\ \ gases)$$

$$\hat{V}_{ideal} > 20L/mol \quad (other\ \ gases)$$

$$\hat{V}_{ideal} = \frac{RT}{P}$$

Non-Ideal Eqns. of State

(that are in the text)

- Virial
  - 1 constant
  - B = f(T_c,P_c, ω)
  - Table 5.3.1 for ω

$$\frac{P\hat{V}}{RT} = 1 + \frac{B}{\hat{V}} \qquad (5.3.2)$$

$$B_0 = 0.083 - \frac{0.42}{T_r^{1.6}}$$

$$B_1 = 0.139 - \frac{0.172}{T_r^{4.2}}$$

$$B = \frac{RT_c}{P_c}\left(B_0 + \omega B_1\right)$$

- Van der Waals
  - 2 constants
  - a & b = f(T_c,P_c)

$$P = \frac{RT}{\hat{V} - b} - \frac{a}{\hat{V}^2} \qquad (5.3.6)$$

$$a = \frac{27R^2T_c^2}{64P_c}$$

$$b = \frac{RT_c}{8P_c}$$

- Soave-Redlich-Kwong (SRK)
  - 3 constants
  - a & b = f(T_c,P_c)
  - α = f(T_c,P_c, ω)

$$P = \frac{RT}{\hat{V} - b} - \frac{a\alpha}{\hat{V}\left(\hat{V} + b\right)} \qquad (5.3.7)$$

$a = 0.42747\ (RT_c)^2/P_c$

$b = 0.08664\ (RT_c)/P_c$

$m = 0.48508 + 1.55171\ \omega - 0.1561\ \omega^2$

$\alpha = [1 + m(1 - T_r^{0.5})]^2$

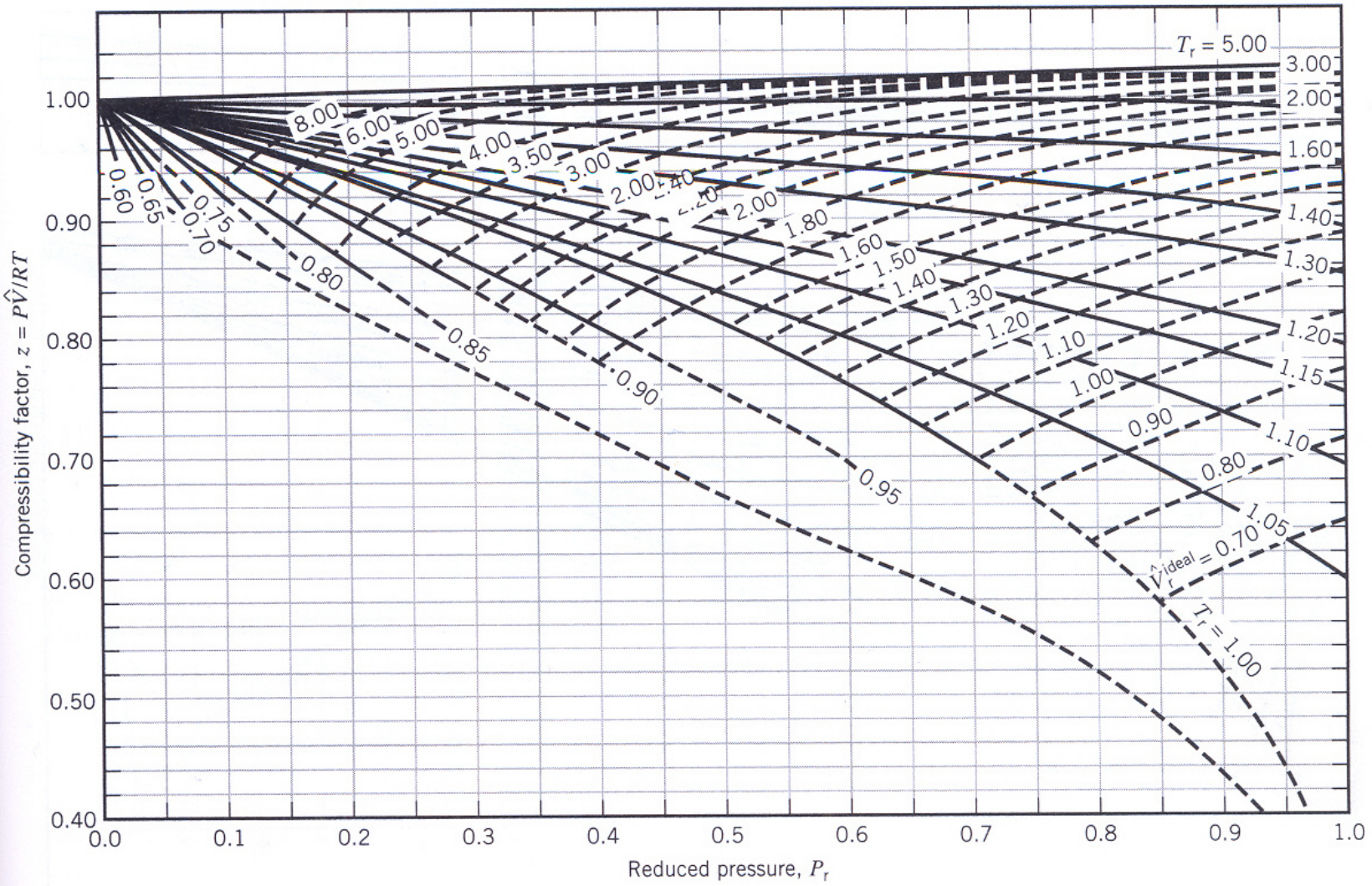


Figure 5.4-2 Generalized compressibility chart, low pressures. (From D. M. Himmelblau, *Basic Principles and Calculations in Chemical Engineering*, 3rd Edition, copyright © 1974, p. 175. Reprinted by permission of Prentice Hall, Inc., Englewood Cliffs, NJ.)

Corresponding States: Mixtures
(Kay's Rule)

Note that these are weighted by mole fraction

$$T_c' = y_A T_{cA} + y_B T_{cB} + y_C T_{cC} + ...$$

$$P_c' = y_A P_{cA} + y_B P_{cB} + y_C P_{cC} + ...$$

$$T_r' = T / T_c'$$

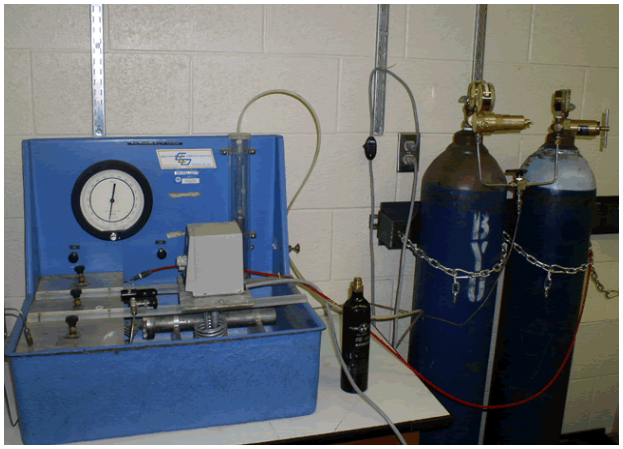
$$P_r' = P / P_c'$$

$z_{tot} \neq \sum y_i z_i$

Hint: We will be using this a lot for mixtures!

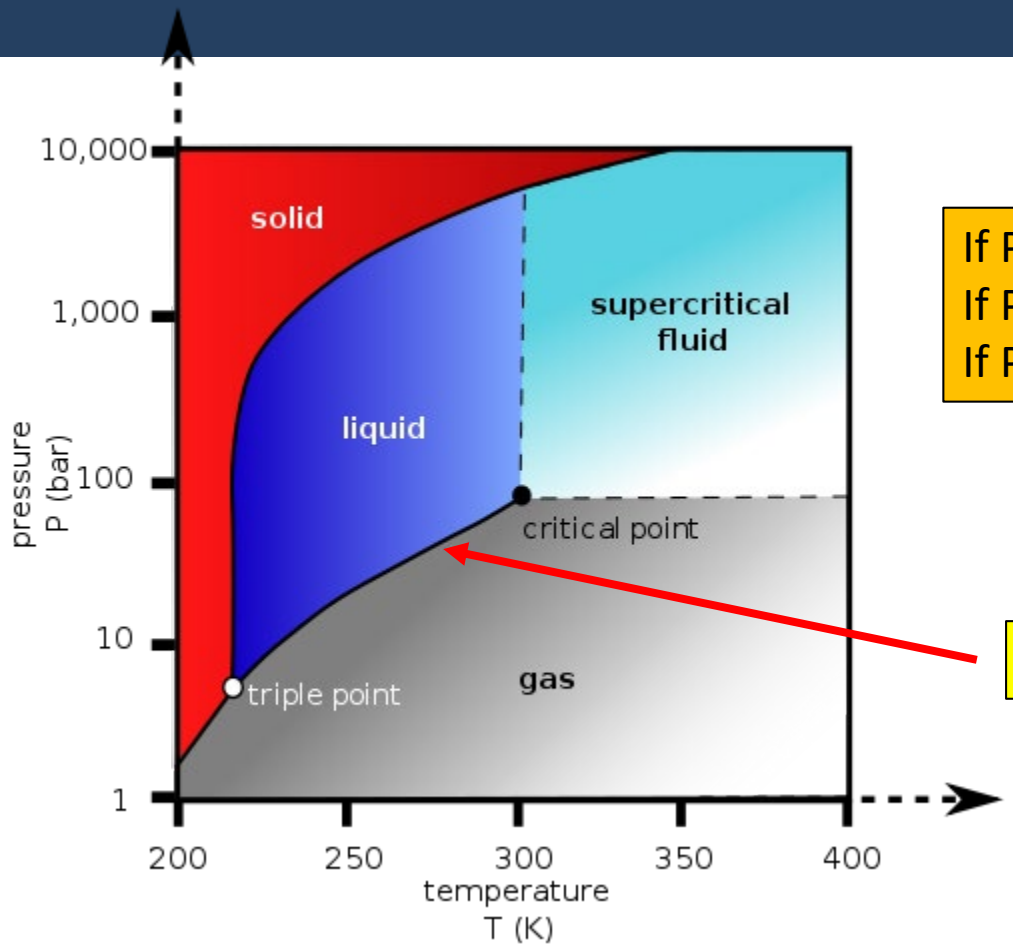
Compressibility Experiment in UO Lab (ChE 475)

- 25% CO_2, 75% Ar
- T = 20°C
- Find z at different pressures



- Compressibility Chart (Law of Corresponding States)
- Kay's Rule for mixture
  - Seniors get mixing rules for non-ideal equations of state from the Thermo class

Phase Diagram

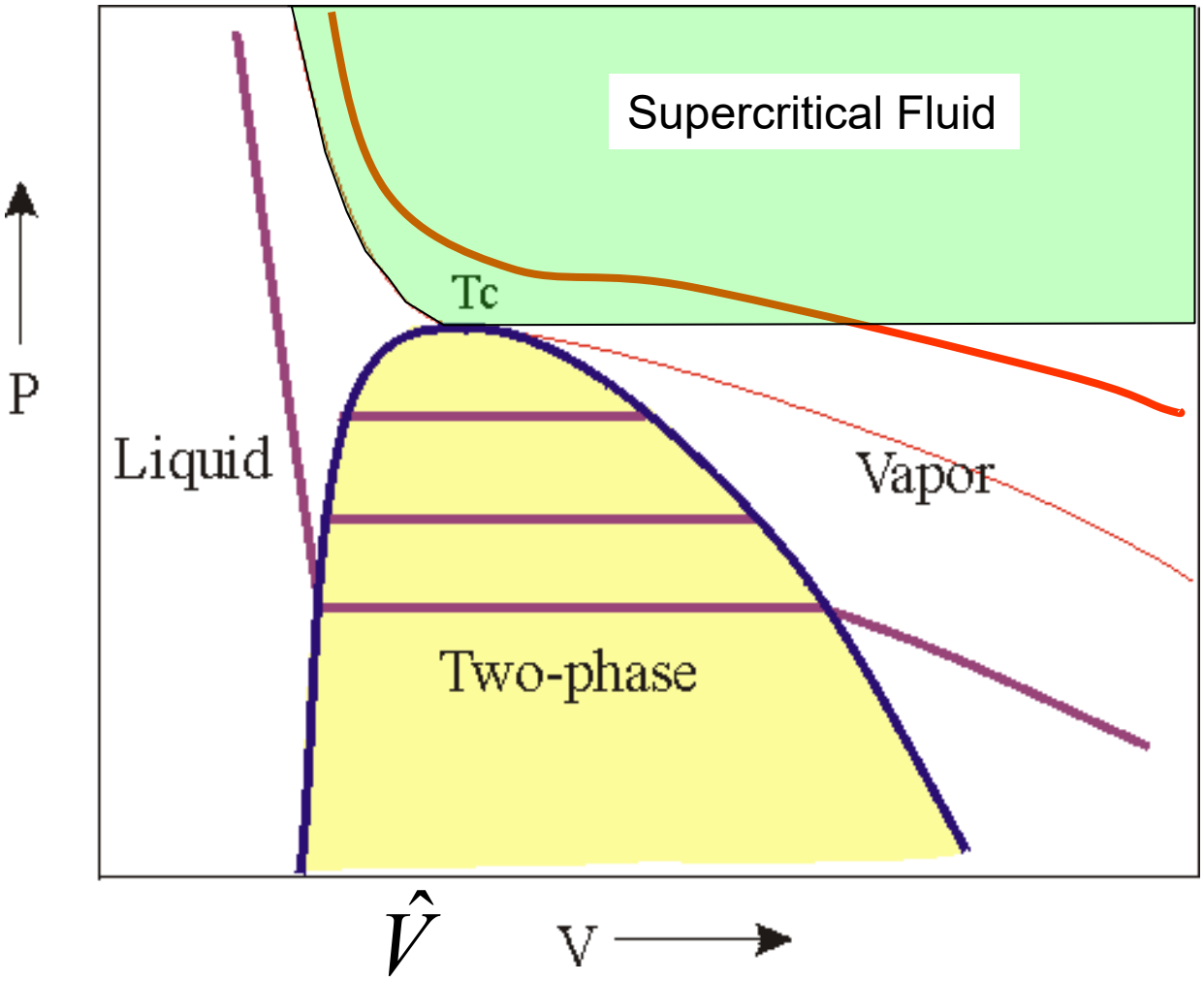


If P > P*, all liquid
If P = P*, 2 phases
If P < P*, all gas

Line is P* vs T

Pressure-temperature phase diagram for CO_2

Phase Diagram for H_2O (Quiz Answers)



1. Please draw
2. Label the following:
   a. 2-phase envelope
   b. Critical point
   c. P_c
3. Draw 3 isotherms
   a. Through 2-phase
   b. Through P_c
   c. Supercritical
4. Label T_c