ENGG 201 - WINTER 2003 – FINAL EXAM

Thursday April 24, 2003
15h30-18h30 (180 minutes)

1. Attempt all **seven (7)** questions
2. Closed Text, Closed Notes, Calculators are allowed.
3. Use the attached formula sheet.
4. Write your name and lecture number below, and put your ID number on each additional page in the blanks provided.

Surname **ANSWER KEY** Given Name(s) ____________________ Section _______

L03 (MWF) Dr. Kallos
L04 (TR) Dr. Hill

Question	Marks
1 - /10	
2 - /15	
3 - /15	
4 - /15	
5 - /15	
6 - /15	
7 - /15	
Total	/100

STUDENT IDENTIFICATION

Each candidate must sign the Seating List confirming presence at the examination. All candidates for final examinations are required to place their University of Calgary student I.D. cards on their desks for the duration of the examination. (Students writing mid-term tests can also be asked to provide identity proof.) Students without an I.D. card who can produce an acceptable alternative I.D., e.g., one with a printed name and photograph, are allowed to write the examination.

A student without acceptable I.D. will be required to complete an Identification Form. The form indicates that there is no guarantee that the examination paper will be graded if any discrepancies in identification are discovered after verification with the student's file. **A Student who refuses to produce identification or who refuses to complete and sign the Identification Form is not permitted to write the examination.**

EXAMINATION RULES

(1) Students late in arriving will not normally be admitted after one-half hour of the examination time has passed:
(2) No candidate will be permitted to leave the examination room until one-half hour has elapsed after the opening of the examination, nor during the last 15 minutes of the examination. All candidates remaining during the last 15 minutes of the examination period must remain at their desks until their papers have been collected by an invigilator.
(3) All enquiries and requests must be addressed to supervisors only.
(4) **Candidates are strictly cautioned against:**
(a) speaking to other candidates or communicating with them under any circumstances whatsoever;
(b) bringing into the examination room any textbook, notebook or memoranda not authorized by the examiner;
(c) making use of calculators and/or portable computing machines not authorized by the instructor;
(d) leaving answer papers exposed to view;
(e) attempting to read other student's examination papers.
The penalty for violation of these rules is suspension or expulsion or such other penalty as may be determined.
(5) Candidates are requested to write on both sides of the pages unless the examiner has asked that the left hand page be reserved for rough drafts or calculations.
(6) Discarded matter is to be struck out and not removed by mutilation of the examination answer book.
(7) Candidates are cautioned against writing in their answer book any matter extraneous to the actual answering of the question set.
(8) The candidate is to write his/her name on each answer book as directed and is to number each book.
(9) A candidate must report to a supervisor before leaving the examination room.
(10) Answer books must be handed to the supervisor-in-charge promptly when the signal is given. Failure to comply with this regulation will be cause for rejection of an answer paper.
(11) If during the course of an examination a student becomes ill or receives word of domestic affliction, the student should report at once to the supervisor, hand in the unfinished paper and request that it be cancelled. If physical and/or emotional ill health is the cause, the student must report at once to a physician/counselor so that subsequent application for a deferred examination is supported by a completed Physician/ Counselor Statement form. Students can consult professionals at University Health Services or University Counseling Services during normal working hours or consult their physician/counselor in the community.
Should a student write an examination, hand in the paper for marking, and later report extenuating circumstances to support a request for cancellation of the paper and for another examination, such a request will be denied.
(12) Smoking during examinations is strictly prohibited.

Question Number I *(10 Marks ~ 18 minutes)*

Use the information below to answer the following questions.

	b_o (m^3 $kmol^{-1}$)	ε/k_b (K)	MW (kg/kmol)
Fluorine (F_2)	0.061492	112.0	38.0
Chlorine (Cl_2)	0.087898	357.0	70.9

a) Calculate the ratio of the bulk density of F_2 (fluorine) to Cl_2 (chlorine) in the solid state if their packing is face-centred cubic (FCC) using the Lennard Jones parameter σ as representative of the diameters of the two diatomic molecules.

From $b_o = \frac{2\pi}{3}\sigma^3 N_A$, *calculate* $\sigma(F_2) = 3.6530 \times 10^{-10}$ *m, and* $\sigma(Cl_2) = 4.1150 \times 10^{-10}$ *m*

Density: $FCC\ materials = \frac{\sqrt{2}m}{d^3}$, $\frac{\rho_{F_2}}{\rho_{Cl_2}} = \frac{m_{F2}}{m_{Cl2}} x \frac{d^3_{Cl2}}{d^3_{F2}} = \frac{38.0}{70.9} x \frac{(4.115)^3}{(3.653)^3} = 0.766$

Therefore, the ratio of the bulk densities is 0.766.

b) Would the bulk density ratio change if both substances were a different cubic structure (i.e., simple cubic or BCC)? Yes or No (circle one)

No, because all ratios reduce to $\frac{m_{F2}}{m_{Cl2}} x \frac{d^3_{Cl2}}{d^3_{F2}}$

c) Calculate the ratio of the force of attraction between two fluorine molecules and the force of attraction between two chlorine molecules if the two molecules in each pair are separated by a distance of r=1.5σ.

$$F(r) = \frac{d\Phi(r)}{dr} = \frac{24\varepsilon\sigma^6}{r^7} - \frac{48\varepsilon\sigma^{12}}{r^{13}},\quad F_a(r) = \frac{24\varepsilon\sigma^6}{r^7} = \frac{24\varepsilon\sigma^6}{(1.5\sigma)^7} = \frac{24\varepsilon}{(1.5)^7\sigma}$$

$$\frac{F_a(F_2)}{F_a(Cl_2)} = \left(\frac{\varepsilon}{\sigma}\right)_{F2} x \left(\frac{\sigma}{\varepsilon}\right)_{Cl2} = \left(\frac{\varepsilon/k_b}{\sigma}\right)_{F2} x \left(\frac{\sigma}{\varepsilon/k_b}\right)_{Cl2} = \frac{112.0}{357.0} x \frac{4.1150}{3.6530} = 0.353$$

Therefore, the ratio of the forces of attraction is 0.353.

d) Calculate the ratio of the net force between fluorine molecules and the net force between chlorine molecules at a distance of r=1.5σ.

$$F(r) = \frac{d\Phi(r)}{dr} = \frac{24\varepsilon\sigma^6}{r^7} - \frac{48\varepsilon\sigma^{12}}{r^{13}} = \frac{24\varepsilon\sigma^6}{(1.5\sigma)^7} - \frac{48\varepsilon\sigma^{12}}{(1.5\sigma)^{13}} = \frac{\varepsilon}{\sigma}\left(\frac{24}{(1.5)^7} + \frac{48}{(1.5)^{13}}\right)$$

$$\frac{F(F_2)}{F(Cl_2)} = \left(\frac{\varepsilon}{\sigma}\right)_{F2} x \left(\frac{\sigma}{\varepsilon}\right)_{Cl2} = \left(\frac{\varepsilon/k_b}{\sigma}\right)_{F2} x \left(\frac{\sigma}{\varepsilon/k_b}\right)_{Cl2} = \frac{112.0}{357.0} x \frac{4.1150}{3.6530} = 0.353$$

Therefore, the ratio of the net forces is 0.353.

Question Number II *(15 Marks ~ 27 minutes)*

Please use the attached phase diagram to answer the following questions.

a) What is the maximum solubility of carbon in α-iron?

0.025 mass% C – read from graph

b) What is the lowest temperature that a 1.0%C mixture could exist as a single phase?

800°C – read from graph

c) A mixture with 19.5 kg of iron and 0.5 kg of carbon is held at a temperature of 725°C.

i) What is the mass percent carbon in the mixture?

0.5 kg / (0.5 + 19.5) = 2.5% (or 0.025)

ii) Name the phases present and their compositions.

Two phases – Ferrite (0.025 mass%C) and Cementite (6.69 mass%C) – read from graph

iii) What is the mass fraction of pearlite in the mixture?

$$\frac{m_p}{m_T} = \frac{w_c - w_m}{w_c - w_p} = \frac{6.69 - 2.5}{6.69 - 0.77} = 0.707$$

iv) What is the mass fraction of free cementite in the mixture?

$$\frac{m_{fc}}{m_T} = \frac{w_m - w_p}{w_c - w_p} = \frac{2.5 - 0.77}{6.69 - 0.77} = 0.293$$

v) What is the total mass of cementite in the mixture?

$$\frac{m_c}{m_T} = \frac{w_m - w_f}{w_c - w_f} = \frac{2.5 - 0.025}{6.69 - 0.025} = 0.371$$

*m_c = 0.371 * 20 kg = 7.43kg*

d) The mixture in (c) is heated up to 1000°C. Name the phases that are now present.

Two phases – Austenite and Cementite

e) What mass of iron must be added to the mixture at 1000°C so that only one phase is present?

New mass%C = 1.6% = 0.016 = (0.5 kg) / (20 kg + m_a)

Solving for m_a = 11.25 kg

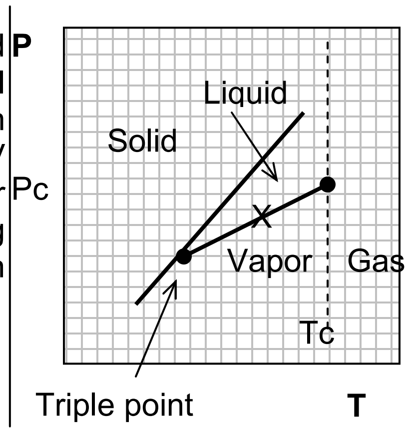
Question Number III *(15 Marks ~ 27 minutes)*

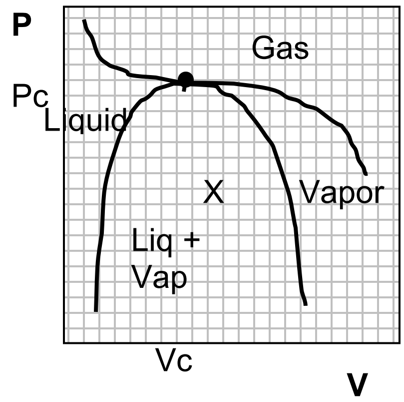
Use the data at the right as well as the triple point of nitrogen (63.15 K, 12.46 kPa) to answer the following questions.

	Nitrogen (N_2)	Oxygen (O_2)
M (kg/kmol)	28	32
Tc (K)	126.2	154.6
Pc (atm)	33.5	49.8
Vc (m^3/kmol)	0.0896	0.0733

a) Nitrogen (2.8 kg) is held in a 10 L container at -173°C and 1.75 MPa.

i) Draw and completely label a PT diagram and a PV diagram for nitrogen using the given information.





ii) Locate the point representing the nitrogen in the 10 L container on both your diagrams. What phase or phases are present in the container?

n=m/M=2.8kg/ 28kg/kmol=0.1 kmol *v=10 L = 0.01 m^3*

V_m=0.01m^3/0.1kmol=0.1m^3/kmol

P=1.75x10^3kPa = 17.27atm *See X on diagram – two phases-L+V*

b) A mixture of liquid and vapor made up of 16 kilograms of oxygen and 42 kg of nitrogen are maintained at a temperature of -160°C and a pressure of 11.65 atm in a rigid steel storage cylinder 5 m high. Please use the attached compressibility chart to answer the following questions.

i) Determine the specific volumes of the liquid and vapor phases using the Law of Corresponding States.

n=m/M=16kg/ 32kg/kmol=0.5 kmol O2 *0.25*

n=m/M=42kg/ 28kg/kmol=1.5 kmol N2 *0.75*

T_{PC}=0.25(154.6)+0.75(126.2)=133.3K

P_{PC}=0.25(49.8)+0.75(33.5)=37.575atm

$$\left.\begin{array}{l} T_r=113.15/133.3=0.85 \\ P_r=11.65/37.575=0.31 \end{array}\right\} \quad \begin{array}{l} Z_L=0.05 \\ Z_V=0.77 \end{array}$$

*V=ZRT/P=0.05*8.314*113.15/(11.65*101.25)=0.040 m^3/kmol LIQUID*

*V=ZRT/P=0.77*8.314*113.15/(11.65*101.25)=0.614 m^3/kmol VAPOUR*

ii) Determine the diameter of the cylinder if the vapor makes up 50% of the moles within the cylinder.

n_T= 0.5 kmol +1.5 kmol = 2.0 kmol *n_v= 0.5*2 = 1 kmol = n_l*

v = v_l+v_v = (n_l)(V_l)+(n_v)(V_v) = (1 kmol)(0.04 m^3/kmol) + (1 kmol)(0.614 m^3/kmol) = 0.654 m^3

$$v = \pi r^2 h = \frac{\pi}{4} d^2 h$$

$$d = \sqrt{\frac{4v}{\pi h}} = \sqrt{\frac{(4)(0.654\,m^3)}{(\pi)(5\,m)}} = 0.408\,m$$

Question Number IV *(15 Marks ~ 27 minutes)*

The normal boiling point of Substance A is 80°C and the latent heat of vaporization is 25,000 kJ/kmol. The normal boiling point of Substance B is 120°C, and its vapor pressure is 2 atm at 150°C. The vapor pressure of Substance C is given by $\ln(P_v)=15.4-3400/T$, where T is in K and P_v is in kPa.

a) Develop a correlation of the form $\ln(P_v)=C_1-C_2/T$ for the vapor pressure as a function of temperature for Substance A (i.e. find the values of C_1 and C_2).

$C_2=\Delta H_v/R=25000/8.314=3006.98K$

$T=80C = 353.15\ K$, $P_v=101.325\ kPa$

$\ln(101.325)=C_1-3006.98/353.15$

Solving for $C_1=13.13$

b) Calculate the vapor pressure of each substance (A, B and C) at 120°C.

A, $\ln(P_v)=13.13-3006.98/393.15$ $P_v=240.96\ kPa$

B, Normal Boiling Point $P_v=101.325kPa$

C, $\ln(P_v)=15.4-3400/393.15$ $P_v=309.35\ kPa$

c) A container holds a vapor-liquid mixture of A, B, and C in equilibrium at 120°C. The vapour contains 10% A and 25% B on a molar basis. Calculate the dew point pressure of the vapor mixture.

Vapour $y_1=0.10$, $y_2=0.25$, $y_3=0.65$

From Raoult's Law we know that $\overline{p_i} = P_{V_i} x_i$

We also know that $\overline{p_i} = P\, y_i$

Thus, $P_{V_i} x_i = P y_i \quad \rightarrow \quad x_i = \dfrac{P y_i}{P_{V_i}}$

Since $\Sigma x_i=1.0$

$$\frac{P\,y_1}{P_{V_1}} + \frac{P\,y_2}{P_{V_2}} + \frac{P\,y_3}{P_{V_3}} = 1.0$$

Using the P_v values from part (b) at 120°C

Solve for P=200.663 kPa

d) Calculate the mole fractions of all three components in the liquid phase.

$x_1=Py_1/Pv_1=0.083$ A

$x_2=Py_2/Pv_2=0.495$ B

$x_3=Py_3/Pv_3=0.422$ C

Question Number V *(15 Marks ~ 27 minutes)*

A viscosity test performed on some Super Liquid Cheese Spread at the Krafty Factory using a Fann viscometer at 90°C generated the following data:

Speed (rpm)	Speed Factor (S) (dimensionless)	θ = dial reading (degrees)
30	10	23
60	5.0	85

The viscometer has been calibrated so that the viscosity can be calculated from $\mu = S\theta f$ where μ=viscosity (Pa.s), S=speed factor, θ=dial reading (degrees), and f=viscometer constant. For this particular instrument, f=0.8229.

a) Determine the viscosity at each of the two speeds.

*$\mu = S\theta f$ =10*23*0.8229=189.3 Pa.s at 30rpm*
*$\mu = S\theta f$ =5*85*0.8229=349.7 Pa.s at 60rpm*

b) Calculate the shear rate and shear stress at each of the speeds. The shear rate (s^{-1}) can be calculated by multiplying the speed (rpm) by 1.5.

*du/dy=1.5*30=45s^{-1} at 30rpm* *$\tau=\mu_{app}$*(du/dy)=189.3*45=8517 Pa at 30 rpm*
*du/dy=1.5*60=90s^{-1} at 60rpm* *$\tau=\mu_{app}$* (du/dy)=349.7*90=31475 Pa at 30 rpm*

c) Determine the power law parameters for the Super Liquid Cheese Spread.

$$\tau = K\left(\frac{du}{dy}\right)^n$$ *log(τ)=log(K)+n*log(du/dy)*

Two equations and two unknowns – sub in τ anddu/dy values from part (b)

K = 6.495 Pa.$s^{1.885}$ *n=1.885*

d) The liquid cheese (μ=90 Pas, ρ=1400 kg/m^3) is to be pumped through 85 cm of smooth stainless steel pipe 1 cm in diameter from a storage tank to a machine that fills glass jars. The outlet from the storage tank (where the pump is located) is 25 cm below the opening in the jars. What power of pump must be used if the machine can fill 15 - 350 mL jars a minute? Assume that the inlet to the pump and the outlet at the jars are both at atmospheric pressure.

*Q=15*350mL/60s=87.5 mL/s -> 8.75x$10^{-5}$$m^3$/s*
A=πr^2=7.85x$10^{-5}$$m^2$ *u=Q/A=1.11m/s* *Re=Duρ/μ=0.173 (laminar)*

$$-\left[\frac{\Delta P}{L} + \rho g\frac{\Delta h}{L}\right] = \frac{32\mu\bar{u}}{D^2}$$ *L=0.85m, Δh=0.25m*

Solve for ΔP = 27.3x10^6Pa *Across pump ΔP = -27.3x10^6Pa*

*Power=QΔP =-27.3x10^6Pa * 8.75x$10^{-5}$$m^3$/s =- 2386 W (negative means power consumed)*

Question Number VI *(15 Marks ~ 27 minutes)*

Dry ice is solid carbon dioxide (CO_2) with a sublimation temperature of -78.44ºC at atmospheric pressure and a heat of sublimation of 25.23 kJ/mol at this temperature. Ten kilograms of dry ice are put in an aluminum cubic vessel of volume 0.00641 m^3. The wall thickness is 2 mm and the thermal conductivity of aluminum is 200 $Wm^{-1}K^{-1}$.

a) What is the amount of heat transferred through the walls of the vessel if the temperature outside of the vessel is 20°C and the heat transfer is uniform through all walls of the vessel?

Volume of cube = 0.00641 m^3 = a^3 $\Rightarrow$ a = 0.18576 m and area = 6 x a^2 = 0.20704 m^2

$$Q = -\kappa A \frac{\Delta T}{\Delta x} = -200 \frac{W}{m \cdot K} x \frac{0.207 m^2 (-98.44K)}{0.002m} = 2.0381 x 10^6 W$$

Therefore, the amount of heat transferred is 2.04 x 10^6 W.

b) If all of the heat transferred causes the dry ice to sublime, how long will it take until the solid is completely changed into gas at –78.44°C?

$$E = Qt = \Delta H_s m, \ t = \frac{\Delta H_s m}{Q} = \frac{25.23 x 10^3 J/mol \cdot 10000 g \cdot 1 mol/44 g}{2.04 x 10^6 J/s} = 2.81 s$$

Therefore, the time until the solid is changed into gas is 2.81 s.

c) What is the rate of heat transfer across the walls of the vessel if a 2 cm layer of polyurethane foam (thermal conductivity = 0.05 $Wm^{-1}K^{-1}$) is added to the vessel?

$$Q = \frac{A \ \Delta T}{\left[\frac{\Delta x_1}{\kappa_1} + \frac{\Delta x_2}{\kappa_2} \right]} = \frac{0.207 m^2 \cdot 98.44 K}{\frac{0.002 m}{200 W/m \cdot K} + \frac{0.02 m}{0.05 W/m \cdot K}} = 50.941 W$$

Therefore, the amount of heat transferred is 50.94 W.

d) How long will it take until all the dry ice sublimes in the insulated vessel and becomes gas at –78.44°C?

$$t = \frac{\Delta H_s m}{Q} = \frac{25.23 x 10^3 J/mol \cdot 10000 g \cdot 1 mol/44 g}{50.941 J/s} = 1.1256 x 10^5 s = 1876 \min = 31.3 h$$

Therefore, the time until the solid is changed into gas in the insulated vessel is 31.3 h.

Question Number VII *(15 Marks ~ 27 minutes)*

a) Consider a solid mild steel cylinder (with Young's modulus E=206.8 GPa and Poisson's ratio ν=0.26), 5 cm in diameter and 2 m long.

i) Mild steel reaches its yield point at 200 MPa. Calculate the force required to produce this pressure on the cylinder.

$$F = PA = P\cdot(2\pi r^2 + 2\pi rl) = 200x10^3\,Pa(2\pi(0.05m/2)^2 + 2\pi(0.05m/2)2m) = 6.362x10^4\,N$$

Therefore, the force required is 63.62 kN.

ii) Calculate what fractional volume change will occur if a pressure of 200 MPa is applied to the cylinder.

$$K = \frac{E}{3(1-2\upsilon)} = \frac{206.8GPa}{3(1-2(0.26))} = 143.61GPa$$
$$\frac{\Delta V}{V} = -\frac{P}{K} = -\frac{200MPa}{143.61x10^3\,MPa} = -0.0013926$$

Therefore, the fractional volume change is -0.00139.

iii) Calculate the final radius of the cylinder (to 4 significant digits) if 200 MPa of pressure is exerted on the cylinder. Consider only radial contraction and ignore contraction along the length of the rod.

$$\frac{\Delta V}{V} = \left(\frac{\pi r_f^2 l - \pi r_i^2 l}{\pi r_i^2 l}\right) = \left(\frac{r_f^2 - r_i^2}{r_i^2}\right)$$

rearranging, $r_f^2 = r_i^2(\frac{\Delta V}{V} + 1) = (5cm/2)^2(-0.0013926 + 1) \Rightarrow r_f = 2.4983cm$

Therefore, the final radius of the cylinder is 2.498 cm.

iv) Calculate the final radius of the cylinder (with 4 significant digits) if it was made out of aluminum (with Young's modulus E=68.9 GPa and Poisson's ratio ν=0.33) instead of mild steel.

$$K = \frac{E}{3(1-2\upsilon)} = \frac{68.9GPa}{3(1-2(0.33))} = 67.54GPa\,,\ \frac{\Delta V}{V} = \left(\frac{r_f^2 - r_i^2}{r_i^2}\right)$$
$$r_f^2 = r_i^2(\frac{-P}{K} + 1) = (5cm/2)^2(\frac{-200MPa}{67.54x10^3\,MPa} + 1) \Rightarrow r_f = 2.4963cm$$

Therefore, the final radius of the cylinder is 2.496 cm.

b) Instead of the pressure being applied as a normal stress, an equivalent (i.e., 200 MPa) shear stress is applied to the mild steel cylinder.

i) Calculate the modulus of rigidity.

$$G = \frac{E}{2(1+\upsilon)} = \frac{206.8GPa}{2(1+0.26)} = 82.063GPa$$

Therefore, the modulus of rigidity is 82.06 GPa.

ii) Calculate the resulting shear strain.

$$\tau = G\gamma \Rightarrow \gamma = \frac{\tau}{G} = \frac{200MPa}{82.063x10^3\,MPa} = 0.0024371$$

Therefore, the resulting shear strain is 0.00244.

FORMULA SHEET

Constants / Conversions

$R = 8.314 \frac{kPa.m^3}{kmol.K} = 8.314 \frac{J}{mol.K}$ $N_A = 6.023x10^{26} \frac{molecules}{kmol}$ $g = 9.81 m/s^2$

$k = 1.3805\ x10^{-23}\ kJ/kmol$ $k = \frac{R}{N_A}$

$101.325\ kPa = 1\ atm$ $1\ bar = 100\ kPa$ $1\ L = 1000\ cm^3$

Phase Rule

F=C+2-P

Geometric Shapes

$V_{sphere} = \frac{4}{3}\pi r^3$ $SA_{sphere} = 4\pi r^2$ $V_{cylinder} = \pi r^2 h$

Ideal Gas

$Pv = nRT$

Kinetic Theory of Gases

$c_{mp} = \sqrt{\frac{2RT}{M}}$ $\sqrt{\overline{c^2}} = \sqrt{\frac{3RT}{M}}$ $\bar{c} = \sqrt{\frac{8RT}{\pi M}}$

$P = \frac{N_A m \overline{c}^2}{3V_m}$ $E_k = \frac{1}{2} m \overline{c}^2$ $k = \frac{R}{N_A}$

$\lambda = \frac{1}{\sqrt{2}\pi\sigma^2 \rho_N}$ $\delta = \left[\frac{kT}{P}\right]^{1/3}$ $\rho_N = \frac{N_A}{V_m} = \frac{kT}{P}$

Kinetic Theory of Gases - Transport Properties

$\mu = \frac{\rho_N \bar{c} \lambda m}{2}$ $\mu = \frac{M}{N_A \pi \sigma^2}\sqrt{\frac{RT}{\pi M}}$

$\kappa = \frac{\lambda \rho_N \bar{c}}{2} \frac{C_v}{N_A}$ $\kappa = \frac{C_v}{N_A \pi \sigma^2}\sqrt{\frac{RT}{\pi M}}$

van der Waals EOS

$P = \frac{RT}{V_m - b} - \frac{a}{V_m^2}$ $V_m^3 - [b + \frac{RT}{P}]V_m^2 + \frac{a}{P}V_m - \frac{ab}{P} = 0$

$P_c = \frac{a}{27b^2}$ $T_c = \frac{8a}{27Rb}$ $V_c = 3b$

$a = \frac{27}{64}\frac{R^2 T_c^2}{P_c}$ $b = \frac{RT_c}{8P_c}$

Mixing Rules >>> $b = \Sigma y_i b_i$ $a = [\Sigma y_i \sqrt{a_i}]^2$

…continued

FORMULA SHEET (continued)

Law of Corresponding States

$$T_r = \frac{T}{T_c} \qquad P_r = \frac{P}{P_c} \qquad PV_m = ZRT$$

Mixtures >>> $T_{pc} = \sum_i y_i T_{ci}, \quad P_{pc} = \sum_i y_i P_{ci}$

Pitzer-Curl $Z = Z^{(0)} + \omega Z^{(1)}$

Vapour-Liquid Equilibrium

$$Pv_i x_i = Py_i = \overline{p}_i \qquad \frac{dP}{dT} = \frac{\Delta Hv}{T(V_g - V_l)}$$

Clapeyron Equation

$$\ln\left(\frac{P_2}{P_1}\right) = \frac{\Delta Hv}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

Viscosity of Liquids

Newtonian

$$\tau = -\mu \frac{du}{dy}$$

Non-Newtonian

$$\mu_{app} = \frac{\tau}{\left(\frac{du}{dy}\right)}$$

Power Law

$$\tau = K\left(\frac{du}{dy}\right)^n$$

Flow of Fluids in Pipes

Reynolds Number

$$\mathrm{Re} = \frac{D\overline{u}\rho}{\mu}$$

Flow Rate

$$Q = \overline{u}A = \overline{u}\frac{\pi D^2}{4}$$

Pump Power

$$Power = Q\Delta P$$

Ideal (Bernoulli)

$$\frac{P}{\rho} + gh + \frac{u^2}{2} = Const.$$

Laminar

$$-\left[\frac{\Delta P}{L} + \rho g \frac{\Delta h}{L}\right] = \frac{32\mu\overline{u}}{D^2}$$

Turbulent

$$-\left[\frac{\Delta P}{L} + \rho g \frac{\Delta h}{L}\right] = \frac{2f\overline{u}^2\rho}{D}$$

Thermal Expansion of Solids

$$\alpha_L = \frac{1}{L}\frac{dL}{dT}$$

Heat Conduction

Fourier's Law

$$Q = -\kappa A \frac{dT}{dx} = -\kappa A \frac{\Delta T}{\Delta x}$$

Composite Planar Wall

$$Q = \frac{A\ \Delta T}{\left[\frac{\Delta x_1}{\kappa_1} + \frac{\Delta x_2}{\kappa_2} + \frac{\Delta x_3}{\kappa_3} + \ldots\right]}$$

Simple Cylinder

$$Q = \frac{2\pi\kappa L\ \Delta T}{\ln\left(\frac{r_2}{r_1}\right)}$$

Composite Cylinder (Pipe)

$$Q = \frac{-2\pi L \Delta T}{\frac{\ln(r_2/r_1)}{\kappa_1} + \frac{\ln(r_3/r_2)}{\kappa_2} + \frac{\ln(r_4/r_3)}{\kappa_3} + \ldots\ldots}$$

…continued

FORMULA SHEET (continued)

Stress and Strain in Solids

Normal Stress

$$\varepsilon = \frac{1}{E}\sigma \qquad \upsilon = -\frac{\varepsilon_x}{\varepsilon_y}$$

$$\varepsilon_x = \frac{1}{E}\sigma_x - \frac{\upsilon}{E}(\sigma_y + \sigma_z) \qquad \varepsilon_y = \frac{1}{E}\sigma_y - \frac{\upsilon}{E}(\sigma_x + \sigma_z) \qquad \varepsilon_z = \frac{1}{E}\sigma_z - \frac{\upsilon}{E}(\sigma_y + \sigma_x)$$

Bulk Modulus for Volume Change

$$\frac{\Delta V}{V} = -\frac{P}{K} \qquad K = \frac{E}{3(1-2\upsilon)}$$

Shear Stress

$$\tau = G\gamma \qquad G = \frac{E}{2(1+\upsilon)}$$

Density of Solids

$$SimpleCubicMaterials = \frac{m}{d^3} \qquad FCC\ materials = \frac{\sqrt{2}m}{d^3} \qquad BCC\ materials = 1.299\frac{m}{d^3}$$

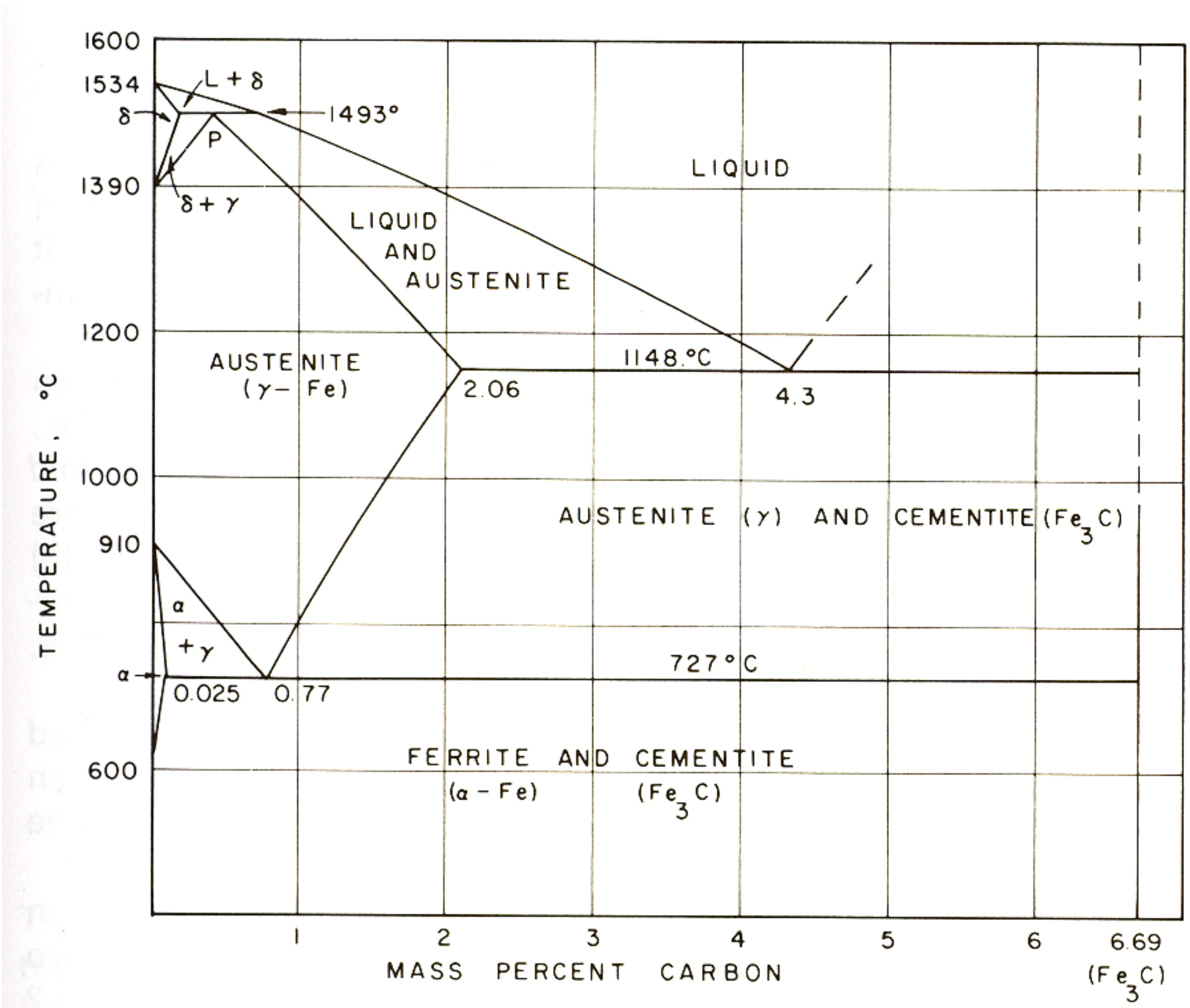
Lennard Jones Potential

$$\Phi(r) = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] \qquad F(r) = \frac{d\Phi(r)}{dr} \qquad \Phi(r) = \int_{\infty}^{r} F(r)dr$$

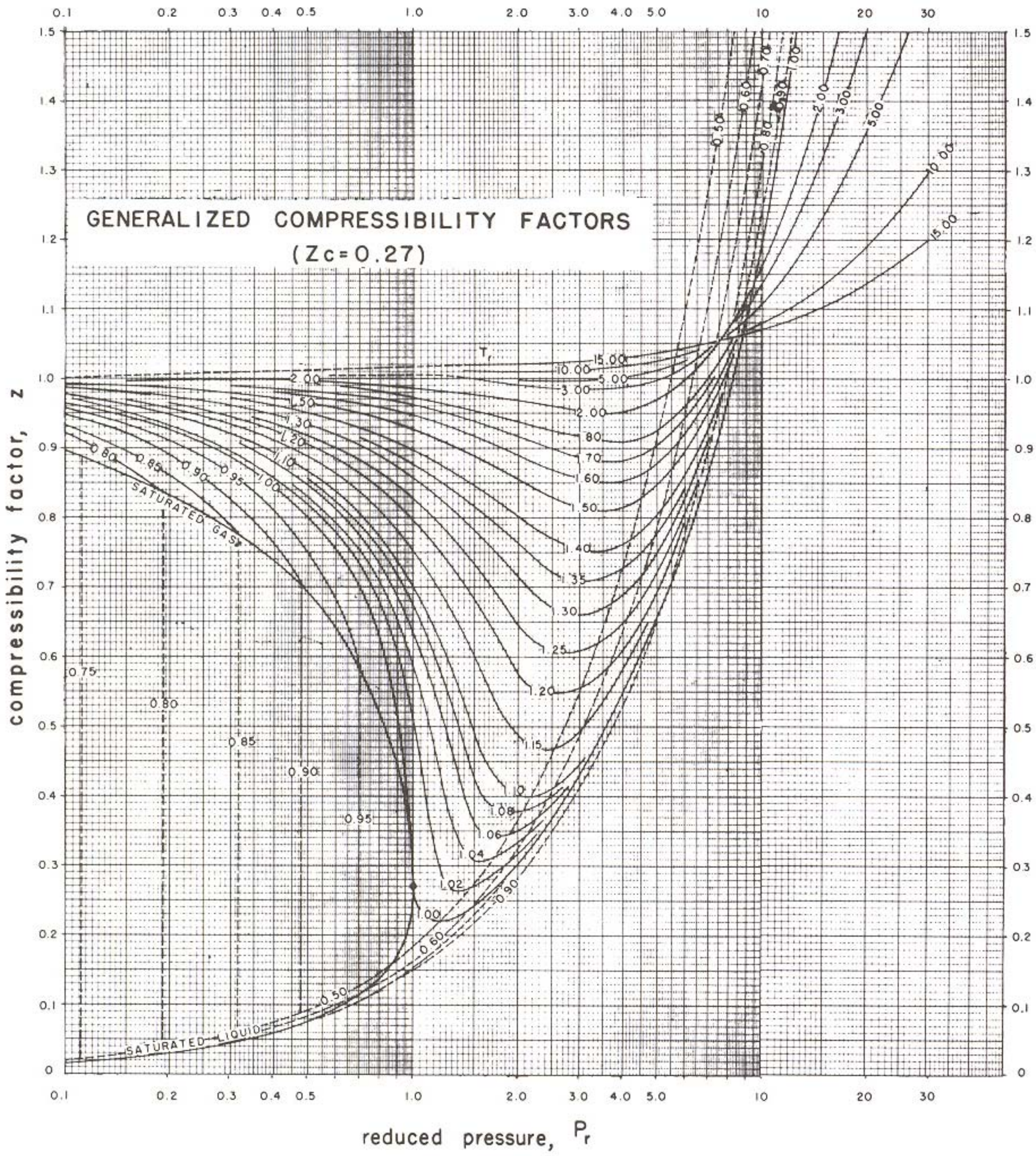
$$\Phi(r) = \Phi(r)_r + \Phi(r)_a$$

$$b_o = \frac{2\pi}{3}\sigma^3 N_A$$

IRON-CARBON PHASE DIAGRAM



GENERALIZED COMPRESSIBILITY CHART



FRICTION FACTOR CHART