Department of

MATERIALS SCIENCE AND ENGINEERING

Doctoral Written Exam

Part II

Friday, January 31, 2003

MichiganEngineering

Department of Materials Science & Engineering

DOCTORAL WRITTEN EXAM
PART II

January 31, 2003

Part II of the Preliminary Examination contains five (5) parts with five (5) questions in each part. You are to submit answers to ten (10) questions for grading. Your final grade will be calculated on the basis of your nine (9) best answers. <u>You may not submit more than four (4) questions from any category</u>.

Please use the answer sheets provided. Staple together **<u>all</u>** pages of your answer for **<u>each</u>** problem, but **<u>do not</u>** staple all the problems together.

Indicate below which problems you are submitting.

Use the same code you used in Part I in place of your name to identify your exam. **<u>Write this code on each and every sheet you submit</u>**. **GOOD LUCK!**

Code Number: ________________

Topic 1 Ceramic Materials

1.________ 2.________ 3.________ 4.________ 5.________

Topic 2 Metallic Materials

1.________ 2.________ 3.________ 4.________ 5.________

Topic 3 Polymer Materials

1.________ 2.________ 3.________ 4.________ 5.________

Topic 4 Thermodynamics & Transport Phenomena

1.________ 2.________ 3.________ 4.________ 5.________

Topic 5 Physics & Physical Properties of Materials

1.________ 2.________ 3.________ 4.________ 5.________

PART II Open Book - Ceramic Materials **CODE # ________**

1.

In fiber reinforced ceramic composites, the fibers are introduced to minimize brittle failure. Sometimes people estimate the strength of the composite by using the rule of mixtures. Provide an equation that shows how one estimates the strength from the rule of mixtures. Explain why this estimate is likely to be wrong--provide clearly defined arguments (this part of the answer is worth 60 % of the question).

PART II Open Book - Ceramic Material **CODE # ________**

2.

The January 2003 issue of the Ceramic Bulletin has a paper on nanomaterials, particularly concerning cerium dioxide CeO_2 and samarium-doped ceria (SDC) of composition $Ce_{0.8}Sm_{0.2}O_{2-x}$. The electrical conductivity of the cerium dioxide at 684°C was 1 S/m, while the SDC had a conductivity of 9 S/m.

a) What crystal structure do you expect for cerium dioxide?

b) How do you expect Sm to be accommodated in ceria (i.e., what site would it occupy?)

c) Why is SDC more conductive than ceria, in terms of defect chemistry and conduction mechanism?

d) What does the “x” mean in $Ce_{0.8}Sm_{0.2}O_{2-x}$?

e) They showed that their 20nm powder can be sintered at 1150°C, while conventional 1000 nm powder sinters at 1500°C. Explain the difference.

PART II Open Book - Ceramic Material **CODE # ________**

3.

Below is a fracture surface of a broken silicon nitride rod.

a) Identify the fracture origin.

b) What is the relationship between the size of the fracture origin and the strength?

c) How can one infer the plane strain fracture toughness by fractography?

Insert Figure

4.

Consider a perfect single crystal of MgO under equilibrium conditions. Show how to evaluate the lattice energy. Explain the use of the Madelung constant. How do the internal energy, the enthalpy and the Gibbs free energy relate to the lattice energy? Assume that the ions constituting the crystal interact according to the function

$$\phi_{ij} = \frac{z_i z_j e^2}{4\pi\varepsilon_0 r_{ij}} + \frac{B_{ij}}{r_{ij}^n},$$

where z_i and z_j are the valences of the ions, $e = 1.602 \times 10^{-19}$ C, $4\pi\varepsilon_0 = 1.113 \times 10^{-10}$ F·m^{-1} and $n = 9$. The lattice parameter of MgO, which crystallizes in the rock salt structure, is 4.2 Å.

PART II Open Book - Ceramic Material **CODE # ________**

5.

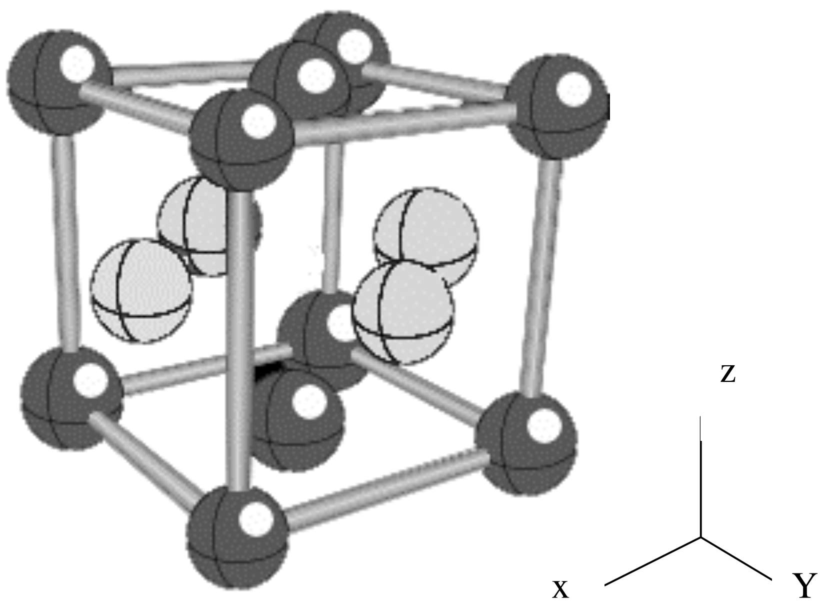
Assuming the velocity of a gas bubble rising in a glass melt is constant, calculate the time necessary for a bubble of 0.1 mm diameter to rise through a layer of melt that is 0.6 m high, when the temperature is 1500 °C, and the viscosity in Nsm^{-2} is given by $\log\eta = \frac{28000}{T} - 8.9$.

Is the answer you get reasonable? How would you proceed to calculate the actual height the bubble has to rise vertically in the bath?

PART II Open Book - Metallic Materials **CODE # ________**

1.

Below is shown the $L1_0$ structure of CuAu. Lattice parameters for this compound are a = 0.402 nm and c = 0.363 nm.



Answer the following questions with respect to this compound.

(a) Identify three types of slip systems that could operate in this material.

(b) Which of the three slip systems identified in part (a) is most likely to be activated during deformation? Justify your answer.

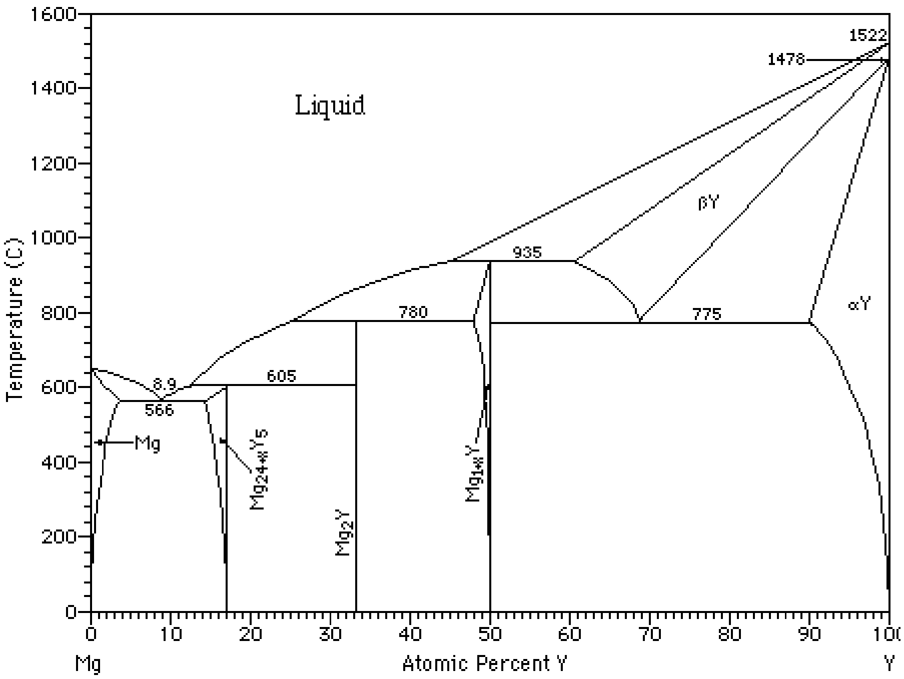
(c) If the critical resolved shear stress for deformation on the slip system identified in (b) is 100 MPa, at what stress will a [001] crystal yield?

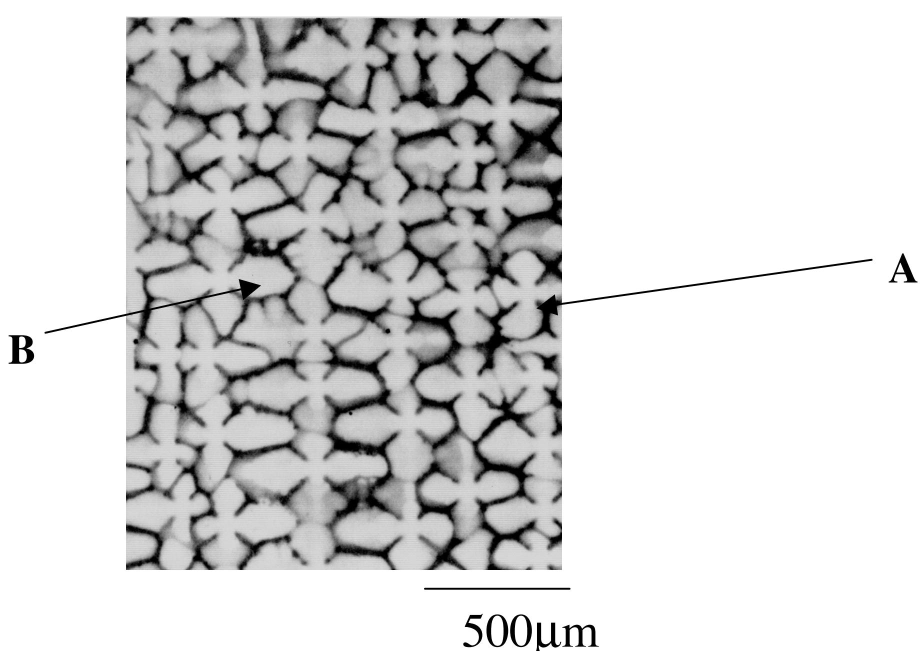
PART II Open Book - Metallic Materials **CODE # ________**

2.

Answer the questions below with regard to a Mg-6at%Y alloy.

(a) A micrograph of this alloy is shown below in as-solidified form. List the composition of the material at points **A** and **B**, assuming no solid state diffusion during cooling.
(b) Describe the changes in the microstructure you would expect to observe if the material were cooled at a faster rate during solidification.
(c) Using the phase diagram, define a heat treatment for homogenization of the alloy shown in the micrograph.
(d) Give an equation and boundary conditions (but do not attempt a solution) that would describe the homogenization process.





PART II Open Book - Metallic Materials **CODE # ________**

3.

An alloy of A - 5% B has a microstructure consisting of an A-rich solid solution and particles of A_2B that are 0.5 μm diameter. Assume that the composition of A_2B is 40% B and that the composition of the A-rich solid solution is 0.01%B. Also assume that A and A_2B have the same density.

a) How many A_2B particles are there per volume?

b) Assuming a simple distribution of these in space, find the distance between particles.

c) Assuming the Orowan equation, find the shear stress required to move dislocations through the material. Take the value of the shear modulus as 25 GPa and the atomic diameter as 0.28 nm.

PART II Open Book - Metallic Materials **CODE # ________**

4.

An engineering component made of an alloy steel is subject to creep under simple tension at a stress of 150 MPa. What is the highest temperature that can be permitted if the component must function for 40 days, and a safety factor of 10 on its life is required? The same material was subjected to creep in a test at 150 MPa at 530ºC, in which it ruptured in 260 hours. (10 points)

PART II Open Book - Metallic Materials **CODE # ________**

5.

Two versions of the copper-lead phase diagram are enclosed with this problem (next page). Use either as needed to answer the following problems. Most problems pertain to a Cu-64 wt% Pb alloy.

a) What phases are present in a Cu-64%Pb alloy at 1100ºC? What are their compositions and in what proportions by weight do they exist? Sketch the microstructure of the alloy in a crucible at this temperature.

b) The alloy is cooled to a temperature just above the three-phase equilibrium temperature of about 954 or 955ºC. What phases are present, what are their compositions, and in what proportions by weight do they exist? Sketch the microstructure in the crucible at this temperature. Take into account that copper and lead have very different densities.

c) What type of three-phase equilibrium reaction occurs at 954 or 955ºC? Write an equation for the reaction.

d) The alloy is now cooled to below this three-phase reaction temperature to just above 326ºC. What phases are present, what are their compositions, and in what proportions by weight do they exist? Sketch the microstructure in the crucible at this temperature.

e) What type of three-phase equilibrium occurs at 326ºC? Write an equation for the reaction.

f) The alloy is now cooled to a temperature below326ºC. What phases are present, what are their compositions, and in what proportions by weight do they exist? Sketch the microstructure in the crucible at this temperature.

Draw curves of Gibbs free energy versus composition for all of the phases which can exist in equilibrium for Cu-Pb alloys of various compositions at 960ºC. Define the reference state(s) used in determining the specific form of each.

PART II Open Book - Polymers **CODE # ________**

1.

Two monodisperse polystyrenes are mixed in equal quantities by weight. One has a molecular weight of 39,000 and the other 292,000. What is the intrinsic viscosity of the blend in benzene at 25°C? The Mark-Houwink constants for polystyrene /benzene are
K =0.0000918 dL/g and a = 0. 74.

2.

A unidirectional fiber composite plate 8 mm thick consists of 63 vol% carbon fiber in an epoxy matrix. In an attempt to reduce material costs, some of the carbon fiber is to be replaced by glass fiber. What **fraction** of the carbon fiber can be replaced if the elastic modulus along the fiber axis is maintained the same but the total fiber volume fraction is allowed to increase to 0.71? The elastic moduli of the fibers and matrix are 245 GPa, 70 GPa, and 5 GPa, respectively, for carbon, glass, and epoxy matrix.

PART II Open Book - Polymers **CODE # ________**

3.

A polymer sample is thought to be a mixture of two polymers, with either or both being crystalline. (a) How might a differential scanning calorimeter be used to determine if the sample is indeed a polymer mixture and what the two polymers might be? (b) What other testing might you do to learn more or confirm your conclusions from differential scanning calorimetry?

PART II Open Book - Polymers **CODE # ________**

4.

The statistics of linear polymer molecules in theta solvents are well described by a scaling relationship of the form:

$$r = an^{1/2}$$

where r is a characteristic size of the chain (such as the radius of gryration), a is a constant, and n is the number of monomer units in the chain. The exponent of 1/2 in this equation is the “ideal” behavior for a polymer chain performing a random walk in three dimensions.

For polymers in good solvents, the energy of a chain was estimated by Flory to have two components: the first due to the stretching of the chain, and the second due to excluded volume interactions. The Flory prediction for the free energy of a chain F can be written as:

$$F = c_1 \frac{n^2}{r^3} + c_2 \frac{r^2}{n}$$

The size of the chain is determined by minimizing this function.

(1) Use this equation to derive a prediction of the exponent of the scaling relationship between n and r for a polymer chain in a good solvent.

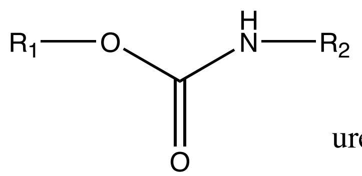
(2) Is a polymer in a good solvent more expanded, less expanded, or similar in expansion to that in a theta solvent?

(3) If a polymer were placed in a non-solvent, it would be expected to collapse into a dense ball (like a ball of string). What would be the exponent in the scaling relationship between the size of the ball r and number of monomer units n?

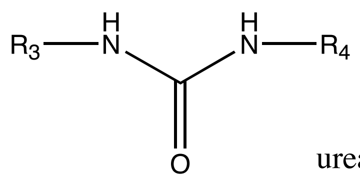
PART II Open Book - Polymers **CODE # ________**

5.

Poly(urethanes) and poly(ureas) are often used in Reaction Injection Molding (RIM). In RIM, the polymers are produced by a chemical reaction directly in the mold from two liquid streams of the molten reactants. Polyurethanes are made by the reaction of an alcohol with an isocyanate, whereas polyureas are made by reacting an amine with an isocyanate.



urethane



urea

(1) Draw the chemical structures of the reactants that were used to prepare the urea and urethane shown above.

(2) What are the condensation products for these reactions?

(3) Why might the condensation products for these reactions influence their choice for use in processing by RIM?

PART II Open Book - Thermodynamics and Transport **CODE # ________**

1.

Use an Ellingham Diagram on the next page to answer this question.

A mixture of methane and water vapor is used in a fuel cell. A practical problem is “coking”, which is the deposition of solid carbon in the fuel input lines at relatively low temperature (600°C).

a) What must the methane/water ratio be to prevent coking?

b) What EMF will be developed at 1000°C if this non-coking mixture is oxidized with air?

PART II Open Book - Thermodynamics and Transport **CODE # ________**

2.

A heat shield is made out of 3 layers of material. The outer layers have thermal conductivities k_1 and thicknesses d_1. The inner layer has thermal conductivities k_2 and thicknesses d_2. If the temperature difference across the shield is ΔT, what is the heat flux through the shield? What is the apparent thermal conductivity of the shield as a whole?

PART II Open Book - Thermodynamics and Transport **CODE # ________**

3.

The following are examples of problems from concepts used to introduce topics in statistical thermodynamics. Answer each of them.

a) What is the probability that two kings will be drawn in succession from a deck of 52 cards?

b) Calculate the probability that upon filling six boxes at random with six objects, one box will contain three objects, three boxes will each contain one, and two boxes will contain no objects.

c) A crystal contains N sites of which N_a sites contain atoms and the remaining sites are vacant. Calculate the entropy of mixing of the occupied and unoccupied sites.

d) Is the process in part (c) an example of Maxwell-Boltzmann, Fermi-Dirac, or Bose-Einstein statistics? Explain briefly.

PART II Open Book - Thermodynamics and Transport **CODE # ________**

4.

Consider a piece of steel containing 0.20% C at 750°C in an atmosphere oxidizing enough to remove all of the carbon from the surface.

a) What is the solubility (wt.%) of carbon in α-iron at 750°C? (1 pt.)

b) Sketch the concentration profile near the surface. (Plot %C vs. distance from surface.) (2 pts.)

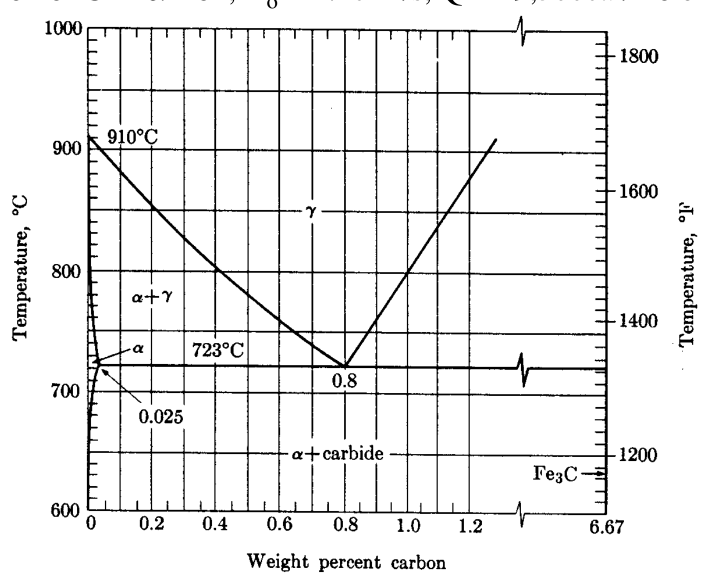
c) Find an appropriate diffusivity for C in iron at 750°C. (1 pt.)

d) Using Fick's first law, J = -Ddc/dx, express the flux, J, in terms of the depth of the decarburized layer. (2 pts.)

e) Write an expression for the depth of the decarburized zone as a function of time. (2 pts.)

f) Evaluate the depth of decarburization after 2.0 hrs. (2 pts.)

For diffusion of C in γ-iron, $D_o = 0.2 cm^2/s$, Q = 34,000cal/mole
For diffusion of C in α-iron, $D_o = 2.2 cm^2/s$, Q = 29,300cal/mole



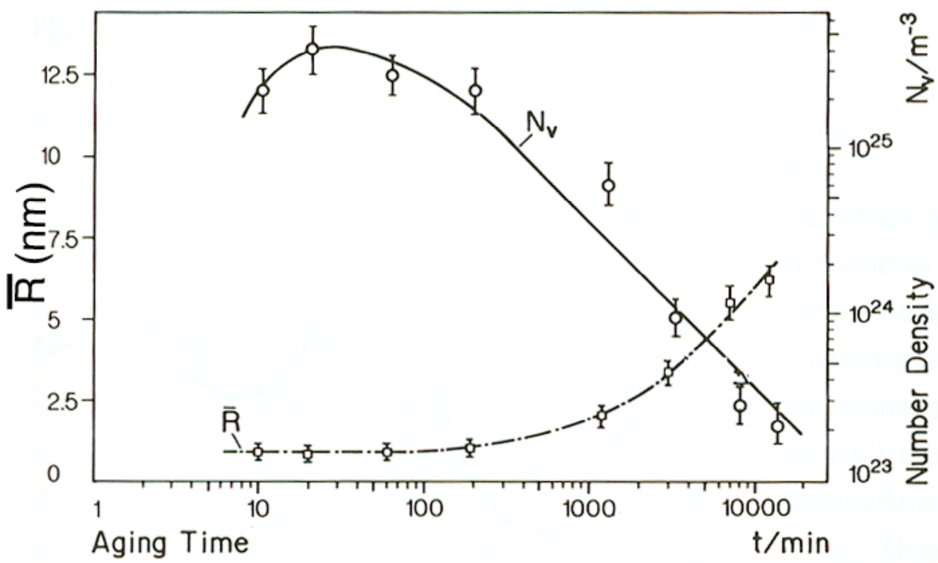
PART II Open Book - Thermodynamics and Transport **CODE # ________**

5.

Below is a plot that displays the typical behavior of a system undergoing homogeneous precipitation.

a) Considering the average radius and number density of precipitates, explain why the curves assume these characteristic shapes. Explicitly discuss the driving forces for change in this system.

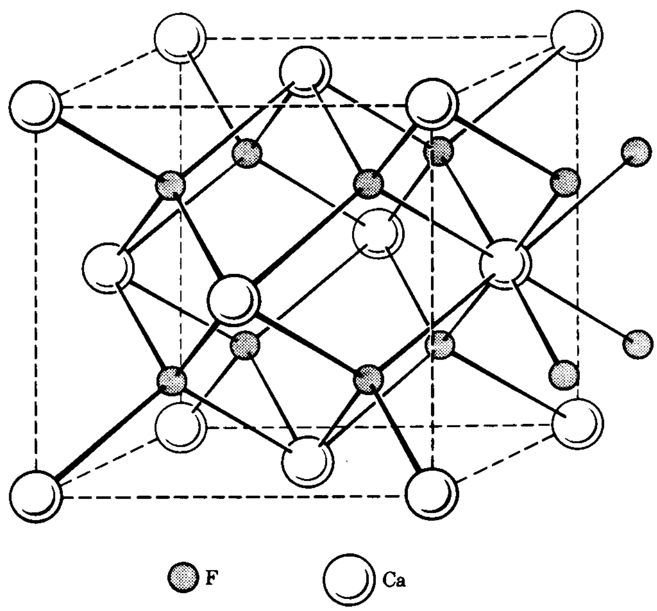
b) Write an expression which describes the evolution of precipitate size for times in excess of 1000 hours. Define the terms in the equation.



PART II Open Book - Physics **CODE # _______**

1.

<u>Structure Factor:</u> Calculate the structure factor of CaF_2 , which has the fluorite structure, shown below. In addition, list the first five reflections which may be present.



PART II Open Book - Physics **CODE # ________**

2.

(a) A doped indium arsenide strip has a thickness 0.15 mm. Using a current of 100 mA through the strip and a magnetic field of 36 mT perpendicular to the strip, the measured Hall voltage was 8.4 mV. Use this data to find the density of charge carriers.

(b) How will your answer in (a) change, given the following data. Show your work!:

I=100 mA

B(mT)	V_H(mV)
17.5	4.4
27	6.4
36	8.4
31	7.4
25	6.1
47	10.9
50	11.5
59.5	13.6

PART II Open Book - Physics **CODE # ________**

3.

Conduction Electrons in Aluminum:

Given the following data for aluminum:

density: 2.70 x 10^3 kg/m^3 at 293K
molar mass: 26.98 g
Fermi Energy: 11.63 eV at 293K

(a) Compute the number of aluminum atoms per unit volume at 293K.

(b) Compute the number density of free electrons at 293K.

(c) Using your answers in (a) and (b), determine the number of conduction electrons per atom. How does this compare with the valence number for aluminum?

4.

Consider an electron moving under the influence of a magnetic field.

a) Explain how the magnetic force acts as a centripetal force on the electron and results in a frequency of oscillation known as the cyclotron frequency. Derive an expression for the cyclotron frequency.

b) What is the cyclotron frequency of an electron at 0.1 Tesla in vacuum?

c) If the cyclotron frequency of an electron in GaAs is 43 GHz what is the ratio of the effective mass of an electron in GaAs to the free electron mass.

5.

Consider the magnetic properties of ferrite ($NiFe_2O_4$) assuming that the magnetization is due only to the Ni^{2+} ions that have eight 3d electrons.

a) Use Hund's rules to determine the values of the total spin angular momentum, S = Σm_s, the total orbital angular momentum, L = Σm_l, and the total angular momentum, J for a Ni^{2+} ion.

b) Assuming that only the spin angular momentum, S, contributes to the magnetization and the molar volume is 4.3×10^{-5} m^{-3}, estimate the magnetization of ferrite in $J/T/m^3$.