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Petzow, G., *Ternary Alloys, A Comprehensive Compendium of Evaluated Constitutional Data and Phase Diagrams*, Wiley, New York, 1988–1995. Fifteen volumes.

Villars, P., A. Prince, and H. Okamoto (Editors), *Handbook of Ternary Alloy Phase Diagrams*, ASM International, Materials Park, OH, 1995. Ten volumes. Also on CD.

QUESTIONS AND PROBLEMS

Solubility Limit

- 9.1 Consider the sugar–water phase diagram of Figure 9.1.
- (a) How much sugar will dissolve in 1000 g of water at 80°C (176°F)?
- (b) If the saturated liquid solution in part (a) is cooled to 20°C (68°F), some of the sugar will precipitate out as a solid. What will be the composition of the saturated liquid solution (in wt% sugar) at 20°C?
- (c) How much of the solid sugar will come out of solution upon cooling to 20°C?
- 9.2 At 100°C, what is the maximum solubility (a) of Pb in Sn? (b) of Sn in Pb?

Microstructure

- 9.3 Cite three variables that determine the microstructure of an alloy.

Phase Equilibria

- 9.4 What thermodynamic condition must be met for a state of equilibrium to exist?

One-Component (or Unary) Phase Diagrams

- 9.5 Consider a specimen of ice that is at -25°C and 10 atm pressure. Using Figure 9.2, the pressure–temperature phase diagram for H_2O , determine the pressure to which the specimen must be raised or lowered to cause it (a) to melt, and (b) to sublime.
- 9.6 At a pressure of 0.1 atm, determine (a) the melting temperature for ice, and (b) the boiling temperature for water.

Binary Isomorphous Systems

- 9.7 Given here are the solidus and liquidus temperatures for the copper–gold system. Construct the phase diagram for this system and label each region.

Composition (wt% Au)	Solidus Temperature ($^{\circ}\text{C}$)	Liquidus Temperature ($^{\circ}\text{C}$)
0	1085	1085
20	1019	1042
40	972	996
60	934	946
80	911	911
90	928	942
95	974	984
100	1064	1064

Interpretation of Phase Diagrams (Binary Isomorphous Systems) (Binary Eutectic Systems) (Equilibrium Diagrams Having Intermediate Phases or Compounds)

- 9.8 Cite the phases that are present and the phase compositions for the following alloys:
- (a) 15 wt% Sn–85 wt% Pb at 100°C (212°F)
- (b) 25 wt% Pb–75 wt% Mg at 425°C (800°F)
- (c) 85 wt% Ag–15 wt% Cu at 800°C (1470°F)
- (d) 55 wt% Zn–45 wt% Cu at 600°C (1110°F)
- (e) 1.25 kg Sn and 14 kg Pb at 200°C (390°F)
- (f) 7.6 lb_m Cu and 144.4 lb_m Zn at 600°C (1110°F)
- (g) 21.7 mol Mg and 35.4 mol Pb at 350°C (660°F)
- (h) 4.2 mol Cu and 1.1 mol Ag at 900°C (1650°F)
- 9.9 Is it possible to have a copper–silver alloy that, at equilibrium, consists of a β phase of composition 92 wt% Ag–8 wt% Cu, and also a liquid phase of composition 76 wt% Ag–24 wt% Cu? If so, what will be the approximate temperature of the alloy? If this is not possible, explain why.
- 9.10 Is it possible to have a copper–silver alloy that, at equilibrium, consists of an α phase of composition 4 wt% Ag–96 wt% Cu, and also a β phase of composition 95 wt% Ag–5 wt%

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- Cu? If so, what will be the approximate temperature of the alloy? If this is not possible, explain why.
- 9.11** A lead–tin alloy of composition 30 wt% Sn–70 wt% Pb is slowly heated from a temperature of 150°C (300°F).
- At what temperature does the first liquid phase form?
 - What is the composition of this liquid phase?
 - At what temperature does complete melting of the alloy occur?
 - What is the composition of the last solid remaining prior to complete melting?
- 9.12** A 50 wt% Ni–50 wt% Cu alloy is slowly cooled from 1400°C (2550°F) to 1200°C (2190°F).
- At what temperature does the first solid phase form?
 - What is the composition of this solid phase?
 - At what temperature does the liquid solidify?
 - What is the composition of this last remaining liquid phase?
- 9.13** For an alloy of composition 52 wt% Zn–48 wt% Cu, cite the phases present and their mass fractions at the following temperatures: 1000°C, 800°C, 500°C, and 300°C.
- 9.14** Determine the relative amounts (in terms of mass fractions) of the phases for the alloys and temperatures given in Problem 9.8.
- 9.15** A 2.0-kg specimen of an 85 wt% Pb–15 wt% Sn alloy is heated to 200°C (390°F); at this temperature it is entirely an α -phase solid solution (Figure 9.8). The alloy is to be melted to the extent that 50% of the specimen is liquid, the remainder being the α phase. This may be accomplished by heating the alloy or changing its composition while holding the temperature constant.
- To what temperature must the specimen be heated?
 - How much tin must be added to the 2.0-kg specimen at 200°C to achieve this state?
- 9.16** A magnesium–lead alloy of mass 7.5 kg consists of a solid α phase that has a composition just slightly below the solubility limit at 300°C (570°F).
- What mass of lead is in the alloy?
 - If the alloy is heated to 400°C (750°F), how much more lead may be dissolved in the α phase without exceeding the solubility limit of this phase?
- 9.17** A 65 wt% Ni–35 wt% Cu alloy is heated to a temperature within the α + liquid-phase region. If the composition of the α phase is 70 wt% Ni, determine:
- The temperature of the alloy
 - The composition of the liquid phase
 - The mass fractions of both phases
- 9.18** A 40 wt% Pb–60 wt% Mg alloy is heated to a temperature within the α + liquid-phase region. If the mass fraction of each phase is 0.5, then estimate:
- The temperature of the alloy
 - The compositions of the two phases
- 9.19** For alloys of two hypothetical metals A and B, there exist an α , A-rich phase and a β , B-rich phase. From the mass fractions of both phases for two different alloys provided in the table below, (which are at the same temperature), determine the composition of the phase boundary (or solubility limit) for both α and β phases at this temperature.

<i>Alloy Composition</i>	<i>Fraction α Phase</i>	<i>Fraction β Phase</i>
70 wt% A–30 wt% B	0.78	0.22
35 wt% A–65 wt% B	0.36	0.64

- 9.20** A hypothetical A–B alloy of composition 40 wt% B–60 wt% A at some temperature is found to consist of mass fractions of 0.66 and 0.34 for the α and β phases, respectively. If the composition of the α phase is 13 wt% B–87 wt% A, what is the composition of the β phase?
- 9.21** Is it possible to have a copper–silver alloy of composition 20 wt% Ag–80 wt% Cu that, at equilibrium, consists of α and liquid phases having mass fractions $W_\alpha = 0.80$ and $W_L = 0.20$? If so, what will be the approximate temperature of the alloy? If such an alloy is not possible, explain why.

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- 9.22** For 5.7 kg of a magnesium–lead alloy of composition 50 wt% Pb–50 wt% Mg, is it possible, at equilibrium, to have α and Mg_2Pb phases with respective masses of 5.13 and 0.57 kg? If so, what will be the approximate temperature of the alloy? If such an alloy is not possible, then explain why.
- 9.23** Derive Equations 9.6a and 9.7a, which may be used to convert mass fraction to volume fraction, and vice versa.
- 9.24** Determine the relative amounts (in terms of volume fractions) of the phases for the alloys and temperatures given in Problems 9.8a, b, and d. Given here are the approximate densities of the various metals at the alloy temperatures:

Metal	Temperature (°C)	Density (g/cm ³)
Cu	600	8.68
Mg	425	1.68
Pb	100	11.27
Pb	425	10.96
Sn	100	7.29
Zn	600	6.67

Development of Microstructure in Isomorphous Alloys

- 9.25 (a)** Briefly describe the phenomenon of coring and why it occurs.
- (b)** Cite one undesirable consequence of coring.

Mechanical Properties of Isomorphous Alloys

- 9.26** It is desirable to produce a copper–nickel alloy that has a minimum noncold-worked tensile strength of 380 MPa (55,000 psi) and a ductility of at least 45% EL. Is such an alloy possible? If so, what must be its composition? If this is not possible, then explain why.

Binary Eutectic Systems

- 9.27** A 60 wt% Pb–40 wt% Mg alloy is rapidly quenched to room temperature from an elevated temperature in such a way that the high-temperature microstructure is preserved. This microstructure is found to consist of the α phase and Mg_2Pb , having respective mass fractions of 0.42 and 0.58. Determine the approximate temperature from which the alloy was quenched.

Development of Microstructure in Eutectic Alloys

- 9.28** Briefly explain why, upon solidification, an alloy of eutectic composition forms a microstructure consisting of alternating layers of the two solid phases.
- 9.29** What is the difference between a phase and a microconstituent?
- 9.30** Is it possible to have a magnesium–lead alloy in which the mass fractions of primary α and total α are 0.60 and 0.85, respectively, at 460°C (860°F)? Why or why not?
- 9.31** For 2.8 kg of a lead–tin alloy, is it possible to have the masses of primary β and total β of 2.21 kg and 2.53 kg, respectively, at 180°C (355°F)? Why or why not?
- 9.32** For a lead–tin alloy of composition 80 wt% Sn–20 wt% Pb and at 180°C (355°F) do the following:
- (a)** Determine the mass fractions of α and β phases.
- (b)** Determine the mass fractions of primary β and eutectic microconstituents.
- (c)** Determine the mass fraction of eutectic β .
- 9.33** The microstructure of a copper–silver alloy at 775°C (1425°F) consists of primary α and eutectic structures. If the mass fractions of these two microconstituents are 0.73 and 0.27, respectively, determine the composition of the alloy.
- 9.34** Consider the hypothetical eutectic phase diagram for metals A and B, which is similar to that for the lead–tin system, Figure 9.8. Assume that: (1) α and β phases exist at the A and B extremities of the phase diagram, respectively; (2) the eutectic composition is 36 wt% A–64 wt% B; and (3) the composition of the α phase at the eutectic temperature is 88 wt% A–12 wt% B. Determine the composition of an alloy that will yield primary β and total β mass fractions of 0.367 and 0.768, respectively.
- 9.35** For a 64 wt% Zn–36 wt% Cu alloy, make schematic sketches of the microstructure that would be observed for conditions of very slow cooling at the following temperatures: 900°C (1650°F), 820°C (1510°F), 750°C (1380°F), and 600°C (1100°F). Label all phases and indicate their approximate compositions.

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- 9.36** For a 76 wt% Pb–24 wt% Mg alloy, make schematic sketches of the microstructure that would be observed for conditions of very slow cooling at the following temperatures: 575°C (1070°F), 500°C (930°F), 450°C (840°F), and 300°C (570°F). Label all phases and indicate their approximate compositions.
- 9.37** For a 52 wt% Zn–48 wt% Cu alloy, make schematic sketches of the microstructure that would be observed for conditions of very slow cooling at the following temperatures: 950°C (1740°F), 860°C (1580°F), 800°C (1470°F), and 600°C (1100°F). Label all phases and indicate their approximate compositions.
- 9.38** On the basis of the photomicrograph (i.e., the relative amounts of the microconstituents) for the lead–tin alloy shown in Figure 9.17 and the Pb–Sn phase diagram (Figure 9.8), estimate the composition of the alloy, and then compare this estimate with the composition given in the figure legend of Figure 9.17. Make the following assumptions: (1) the area fraction of each phase and microconstituent in the photomicrograph is equal to its volume fraction; (2) the densities of the α and β phases as well as the eutectic structure are 11.2, 7.3, and 8.7 g/cm³, respectively; and (3) this photomicrograph represents the equilibrium microstructure at 180°C (355°F).
- 9.39** The room-temperature tensile strengths of pure copper and pure silver are 209 MPa and 125 MPa, respectively.
- (a) Make a schematic graph of the room-temperature tensile strength versus composition for all compositions between pure copper and pure silver. (*Hint*: you may want to consult Sections 9.10 and 9.11, as well as Equation 9.24 in Problem 9.64.)
- (b) On this same graph schematically plot tensile strength versus composition at 600°C.
- (c) Explain the shapes of these two curves, as well as any differences between them.

Equilibrium Diagrams Having Intermediate Phases or Compounds

- 9.40** Two intermetallic compounds, A_3B and AB_3 , exist for elements A and B. If the compositions for A_3B and AB_3 are 91.0 wt% A–9.0 wt% B and 53.0 wt% A–47.0 wt% B, respectively, and element A is zirconium, identify element B.
- 9.41** What is the principal difference between congruent and incongruent phase transformations?
- 9.42** Figure 9.36 is the tin–gold phase diagram, for which only single-phase regions are labeled. Specify temperature–composition points at which all eutectics, eutectoids, peritectics, and congruent phase transformations occur. Also, for each, write the reaction upon cooling.
- 9.43** Figure 9.37 is a portion of the copper–aluminum phase diagram for which only single-phase regions are labeled. Specify temperature–composition points at which all eutectics, eutectoids, peritectics, and congruent phase transformations occur. Also, for each, write the reaction upon cooling.
- 9.44** Construct the hypothetical phase diagram for metals A and B between room temperature (20°C) and 700°C given the following information:
- The melting temperature of metal A is 480°C.
 - The maximum solubility of B in A is 4 wt% B, which occurs at 420°C.
 - The solubility of B in A at room temperature is 0 wt% B.
 - One eutectic occurs at 420°C and 18 wt% B–82 wt% A.
 - A second eutectic occurs at 475°C and 42 wt% B–58 wt% A.
 - The intermetallic compound AB exists at a composition of 30 wt% B–70 wt% A, and melts congruently at 525°C.
 - The melting temperature of metal B is 600°C.
 - The maximum solubility of A in B is 13 wt% A, which occurs at 475°C.
 - The solubility of A in B at room temperature is 3 wt% A.

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Figure 9.36 The tin–gold phase diagram. (Adapted with permission from *Metals Handbook*, 8th edition, Vol. 8, *Metallography, Structures and Phase Diagrams*, American Society for Metals, Metals Park, OH, 1973.)

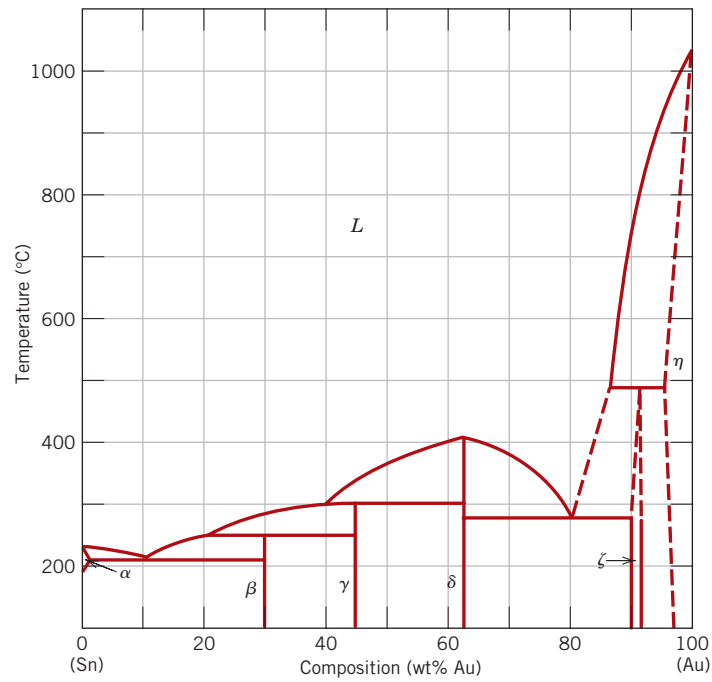


Figure 9.37 The copper–aluminum phase diagram. (Adapted with permission from *Metals Handbook*, 8th edition, Vol. 8, *Metallography Structures and Phase Diagrams*, American Society for Metals, Metals Park, OH, 1973.)

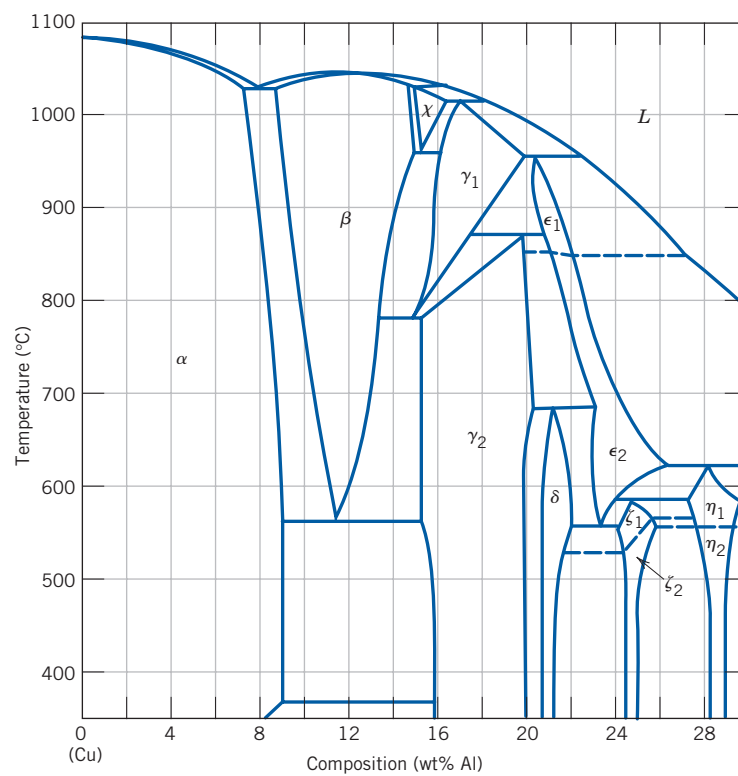
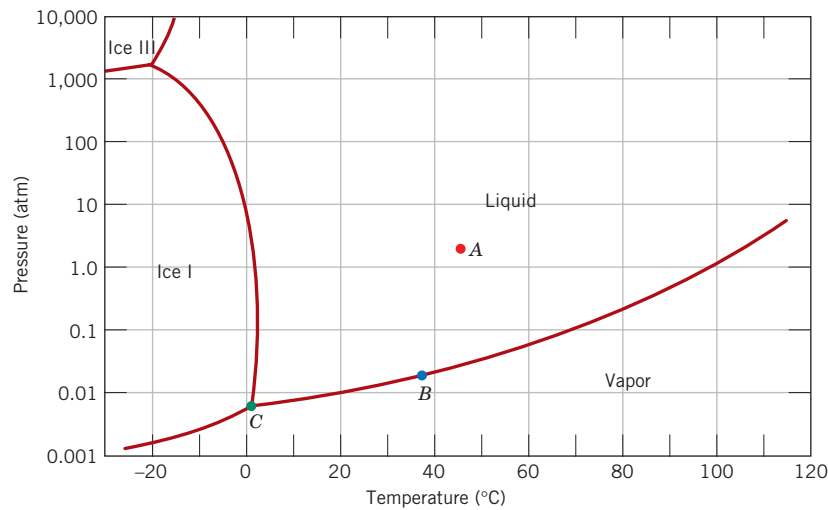


Figure 9.38
Logarithm pressure-
versus-temperature
phase diagram
for H₂O.



The Gibbs Phase Rule

9.45 In Figure 9.38 is shown the pressure–temperature phase diagram for H₂O. Apply the Gibbs phase rule at points *A*, *B*, and *C*; that is, specify the number of degrees of freedom at each of the points—that is, the number of externally controllable variables that need be specified to completely define the system.

The Iron–Iron Carbide (Fe–Fe₃C) Phase Diagram Development of Microstructure in Iron–Carbon Alloys

9.46 Compute the mass fractions of α ferrite and cementite in pearlite.

9.47 (a) What is the distinction between hypoeutectoid and hypereutectoid steels?

(b) In a hypoeutectoid steel, both eutectoid and proeutectoid ferrite exist. Explain the difference between them. What will be the carbon concentration in each?

9.48 What is the carbon concentration of an iron–carbon alloy for which the fraction of total cementite is 0.10?

9.49 What is the proeutectoid phase for an iron–carbon alloy in which the mass fractions of total ferrite and total cementite are 0.86 and 0.14, respectively? Why?

9.50 Consider 3.5 kg of austenite containing 0.95 wt% C, cooled to below 727°C (1341°F).

(a) What is the proeutectoid phase?

(b) How many kilograms each of total ferrite and cementite form?

(c) How many kilograms each of pearlite and the proeutectoid phase form?

(d) Schematically sketch and label the resulting microstructure.

9.51 Consider 6.0 kg of austenite containing 0.45 wt% C, cooled to below 727°C (1341°F).

(a) What is the proeutectoid phase?

(b) How many kilograms each of total ferrite and cementite form?

(c) How many kilograms each of pearlite and the proeutectoid phase form?

(d) Schematically sketch and label the resulting microstructure.

9.52 Compute the mass fractions of proeutectoid ferrite and pearlite that form in an iron–carbon alloy containing 0.35 wt% C.

9.53 The microstructure of an iron–carbon alloy consists of proeutectoid ferrite and pearlite; the mass fractions of these two microconstituents are 0.174 and 0.826, respectively. Determine the concentration of carbon in this alloy.

9.54 The mass fractions of total ferrite and total cementite in an iron–carbon alloy are 0.91 and 0.09, respectively. Is this a hypoeutectoid or hypereutectoid alloy? Why?

9.55 The microstructure of an iron–carbon alloy consists of proeutectoid cementite and pearlite; the mass fractions of these microconstituents

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are 0.11 and 0.89, respectively. Determine the concentration of carbon in this alloy.

- 9.56** Consider 1.5 kg of a 99.7 wt% Fe–0.3 wt% C alloy that is cooled to a temperature just below the eutectoid.
- How many kilograms of proeutectoid ferrite form?
 - How many kilograms of eutectoid ferrite form?
 - How many kilograms of cementite form?
- 9.57** Compute the maximum mass fraction of proeutectoid cementite possible for a hyper-eutectoid iron–carbon alloy.
- 9.58** Is it possible to have an iron–carbon alloy for which the mass fractions of total cementite and proeutectoid ferrite are 0.057 and 0.36, respectively? Why or why not?
- 9.59** Is it possible to have an iron–carbon alloy for which the mass fractions of total ferrite and pearlite are 0.860 and 0.969, respectively? Why or why not?
- 9.60** Compute the mass fraction of eutectoid cementite in an iron–carbon alloy that contains 1.00 wt% C.
- 9.61** The mass fraction of *eutectoid* cementite in an iron–carbon alloy is 0.109. On the basis of this information, is it possible to determine the composition of the alloy? If so, what is its composition? If this is not possible, explain why.
- 9.62** The mass fraction of *eutectoid* ferrite in an iron–carbon alloy is 0.71. On the basis of this information, is it possible to determine the composition of the alloy? If so, what is its composition? If this is not possible, explain why.
- 9.63** For an iron–carbon alloy of composition 3 wt% C–97 wt% Fe, make schematic sketches of the microstructure that would be observed for conditions of very slow cooling at the

following temperatures: 1250°C (2280°F), 1145°C (2095°F), and 700°C (1290°F). Label the phases and indicate their compositions (approximate).

- 9.64** Often, the properties of multiphase alloys may be approximated by the relationship

$$E(\text{alloy}) = E_{\alpha}V_{\alpha} + E_{\beta}V_{\beta} \quad (9.24)$$

where E represents a specific property (modulus of elasticity, hardness, etc.), and V is the volume fraction. The subscripts α and β denote the existing phases or microconstituents. Employ the relationship above to determine the approximate Brinell hardness of a 99.75 wt% Fe–0.25 wt% C alloy. Assume Brinell hardnesses of 80 and 280 for ferrite and pearlite, respectively, and that volume fractions may be approximated by mass fractions.

The Influence of Other Alloying Elements

- 9.65** A steel alloy contains 95.7 wt% Fe, 4.0 wt% W, and 0.3 wt% C.
- What is the eutectoid temperature of this alloy?
 - What is the eutectoid composition?
 - What is the proeutectoid phase?
- Assume that there are no changes in the positions of other phase boundaries with the addition of W.
- 9.66** A steel alloy is known to contain 93.65 wt% Fe, 6.0 wt% Mn, and 0.35 wt% C.
- What is the approximate eutectoid temperature of this alloy?
 - What is the proeutectoid phase when this alloy is cooled to a temperature just below the eutectoid?
 - Compute the relative amounts of the proeutectoid phase and pearlite. Assume that there are no alterations in the positions of other phase boundaries with the addition of Mn.