Resources for Students

using

Separation Process Principles, 2nd Edition

by

J. D. Seader
Table of Contents

1. Study Questions for each chapter .......................... 1

2. Answers to Selected Odd-numbered Exercises .......... 79

3. Problem-solving Techniques ................................. 117

4. Suggestions for Completing Homework Exercises ...... 123
1. Study Questions

To gain the best understanding of the material presented in, “Separation Process Principles”, 2nd Edition, by J.D. Seader and Ernest J. Henley, print these Study Questions and write in your answers as you read.

Chapter 1

Section 1.1:

1. What are the two key process operations in chemical engineering?

2. What are the main auxiliary process operations in chemical engineering?

3. What is the difference between a block flow diagram and a process flow diagram?

4. Why do almost all industrial chemical processes contain separation operations?

5. Why is the espresso machine a good example of a product design based on chemical engineering?

Section 1.2:

6. Is the separation of a mixture a spontaneous, natural process?

7. What are the five general separation techniques and what do they all have in common?

8. Why is mass transfer a major factor in separation processes?

9. What limits the extent to which the separation of a mixture can be achieved?

10. List at least five property differences that can be exploited to develop a separation process.
Section 1.3:

11. What are the two agents that can be used to create a second phase in the separation of a chemical mixture?

12. What is the most common method used to separate two fluid phases?

13. List five separation operations that use an ESA and five that use an MSA.

14. Give three disadvantages of using an MSA.

15. What is the most widely used industrial separation operation?

16. What is extractive distillation? How does it differ from distillation and when should it be considered?

17. What is the difference between absorption and stripping?

18. What is liquid-liquid extraction, when should it be considered, and how does it differ from supercritical-fluid extraction and leaching?

19. What is the basic requirement for removing liquid from a wet solid by evaporation?

20. Why is crystallization important in the semiconductor industry?

Section 1.4:

21. How does the mechanism of separation for a microporous membrane differ from that of a nonporous membrane?

22. Why can't osmosis be used to separate a liquid mixture?

23. How do reverse osmosis and dialysis differ? What do they have in common?
24. How does gas permeation differ from pervaporation?

25. Why are membrane separations important in the human body?

Section 1.5:

26. In the separation of a mixture, how does the action of a membrane differ from that of a solid adsorbent?

27. What is the difference between adsorption and absorption?

28. Adsorption requires that the adsorbed chemicals be separated from the adsorbent to regenerate it and prepare it for reuse. How do pressure-swing adsorption and thermal-swing adsorption differ in the means of regeneration?

Section 1.6:

29. What is the difference between dialysis and electrodialysis?

30. How does field-flow fractionation work from a fluid mechanics standpoint? Can the flow field be turbulent? If not, why not?

Section 1.7:

31. The degree of separation in a separation operation is often specified in terms of component recoveries and/or product purities. How do these two differ?

32. For a separation operation, is it possible to specify the recovery of a feed component and the mole (or mass) fraction of that same component in one of the products?

33. Is the component split fraction the same as the component recovery? If not, how do they differ?

34. What is the difference between the split fraction and split ratio?
35. What is a key component? What is a multicomponent product?

36. Using an aqueous sulfuric acid solution in an example, explain the differences among compositions in terms of molarity, molality, and normality.

**Section 1.8:**

37. What factors of a separation operation influence the degree of separation?

38. What is the separation power?

**Section 1.9:**

39. When selecting a separation method, what factors are important?

40. What five separation operations are the most technologically mature?
Chapter 2

1. What are the three uses of thermodynamics in separation operations?

Section 2.1:

2. Is energy conserved in a separation process?

3. In an energy balance, what are the two most common references (datums) used for enthalpy and entropy? Does one have an advantage over the other?

3. Can the first law of thermodynamics be used to determine energy efficiency?

4. Is entropy conserved in a separation process? If not, is entropy produced or used?

5. What two thermodynamic quantities are a measure of energy inefficiency? Which one is preferred? Why?

6. How does availability differ from Gibbs free energy?

7. Under what conditions can heat be completely converted to shaft work?

8. Under what conditions can a separation process be carried out with a minimum amount of work?

9. How is the second-law efficiency of a separation process defined?

10. Under what conditions can a separation process occur without adding energy in the form of shaft work or heat to the process?

Section 2.2:

11. What are the necessary conditions for phase equilibria?
12. Why is fugacity used in place of chemical potential to determine phase equilibria? Who invented fugacity?

13. How is the $K$-value for vapor-liquid equilibria defined?

14. How is the distribution coefficient for a liquid-liquid mixture defined?

15. What are the definitions of relative volatility and relative selectivity?

16. What are the two most widely used rigorous forms for estimating $K$-values from fugacities and/or activity coefficients? Which one is preferred? Why?

17. What are the assumptions that lead to the Raoult's law $K$-value? Can the Raoult's law $K$-value be used for a component, whose critical temperature is less than the system temperature? If not, what law can be used?

18. Is Henry’s law defined uniquely or are many forms used?

19. At low pressures, when the liquid solution is nonideal, how can the Raoult's law $K$-value be modified?

20. What is the Poynting correction and for what is it used?

Section 2.3:

21. What is the difference between a gas mixture that follows the ideal gas law and an ideal gas solution?

22. Does pressure affect the enthalpy and/or entropy of an ideal gas mixture?

23. What is the most widely used equation for estimating vapor pressure?

24. Can the enthalpy of vaporization be estimated from vapor pressure?

25. What are Raoult's and Dalton's laws? Do they make sense?
Section 2.4:

26. Does liquid density decrease or increase with increasing temperature?

27. Why is the enthalpy of vaporization a function only of saturation temperature and not pressure?

28. What is the convergence pressure of a mixture? Is it the same as the critical pressure of the mixture?

29. How is the effect of composition taken into account in the Hadden-Grayson K-value charts?

30. Why are there no simple charts for estimating liquid-liquid distribution coefficients?

Section 2.5:

31. What are the two types of models used to estimate thermodynamic properties?

32. What are constitutive equations?

33. What is the theorem of corresponding states?

34. What is the acentric factor? Is it interchangeable with the critical compressibility factor as a third parameter for an equation of state?

35. What is meant by a cubic equation of state?

36. What are mixing rules?

37. What is the limitation of the Redlich-Kwong equation of state? How did Wilson and Soave modify it to overcome the limitation?

38. What is the purpose of a binary interaction parameter in a mixing rule? What is its value for pairs of hydrocarbon isomers?
39. How are the S-R-K and P-R equations of state alike and how are they different?

40. What do the B-W-R and L-K-P equations have in common?

41. What thermodynamic properties can be derived rigorously from a $P-v-T$ equation of state?

42. When an equation such as the R-K, S-R-K, or P-R is used to compute the liquid enthalpy referred to ideal gas, is the heat of vaporization automatically taken into account?

43. The R-K equation predicts a single curve for reduced vapor pressure as a function of reduced temperature. Is this also true of the S-R-K and P-R equations? Explain?

44. Do all hydrocarbon mixtures form ideal gas and liquid solutions?

45. Are the S-R-K, P-R, and L-K-P equations capable of predicting the effect of composition, as well as temperature and pressure, on $K$-values?

Section 2.6:

46. Are equations for predicting liquid-phase activity coefficients usually derived from equations of state or from Gibbs free-energy models?

47. How is the liquid-phase activity coefficient defined?

48. How is the liquid-phase activity coefficient related to Gibbs free energy?

49. Deviations from ideal-solution behavior are mainly due to differences in molecular size and intermolecular forces. How are these differences handled in the regular-solution theory?

50. What is meant by a regular solution and what types of chemicals form regular solutions?
51. What is unique about regular-solution theory compared to other activity-coefficient models for nonideal solutions? This difference makes it much easier to use regular-solution theory when it is applicable.

52. For what does the Flory-Huggins theory correct?

53. Why is hydrogen bonding so important in determining the extent of solution nonideality? What kinds of chemicals form hydrogen bonds?

54. Why does a mixture of acetone and chloroform exhibit a negative deviation from Raoult’s law?

55. What causes some mixtures of water and \( n \)-butanol to split into two liquid phases?

56. What is meant by a polar chemical?

57. The major models for estimating a liquid-phase activity coefficient contain only binary interaction parameters. Why are ternary interaction parameters unnecessary or are they?

58. What are the six most widely used methods for estimating liquid-phase activity coefficients?

59. Is the van Laar equation derived from an equation of state or a Gibbs free energy model?

60. What is meant by an activity coefficient at infinite dilution?

61. For what magnitude of infinite-dilution activity coefficient does the van Laar equation predict phase splitting?

62. Binary interaction parameters for activity-coefficient models can be determined from experimental data for: (1) infinite-dilution conditions, (2) azeotropic conditions, or (3) the entire range of composition. What is the preferred type of data?

63. Should the van Laar equation be used for mixtures that exhibit high activity coefficients without phase splitting? What chemicals form such mixtures?
64. What very important concept did Wilson introduce in 1964?

65. Can the Wilson model be used to predict activity coefficients under conditions of phase splitting?

66. What is meant by local, as opposed to average, compositions?

67. Can the Wilson model predict maxima or minima in the activity coefficient? If not, what equation can?

68. Using a modified Raoult's law, what are the conditions for the formation of an azeotrope for a binary mixture?

69. What is a minimum-boiling azeotrope? What is a maximum-boiling azeotrope? Which type is by far the most common?

70. What is the advantage of the NRTL model over the Wilson model?

71. What is the difference between the UNIQUAC and UNIFAC models?

72. Under what conditions does phase splitting occur?

73. What is the thermodynamic criterion for phase splitting?

74. What is the critical solution temperature?

75. What activity-coefficient equations can be used for L-L and V-L-L equilibrium calculations?

**Section 2.7:**

76. What is the P-S-R-K model? For what kind of mixture is it useful?

77. Why must electrolyte-solution activity-coefficient models consider both chemical and physical equilibrium?
78. Under what conditions can the NRTL model be used to predict liquid-phase activity coefficients of a mixture containing polymer, monomer, and a solvent?

Section 2.8:

79. When selecting an appropriate method for estimating \( K \)-values for the components in a mixture, how should the mixture be characterized?

80. If the mixture is an aqueous electrolyte solution, what method is suitable for estimating activity coefficients?

81. If the mixture contains hydrocarbons that cover a wide range of normal boiling point, what \( K \)-value method is preferred?

82. For mixtures of organic compounds, including some components that are polar, what methods are suitable for estimating \( K \)-values?

83. When should the Peng-Robinson and Soave-Redlich-Kwong methods for estimating \( K \)-values be used?
Chapter 3

1. In chemical engineering, does mass transfer refer to the relative movement of chemical species in a mixture or the flow rate of the entire mixture?

2. What is meant by diffusion?

3. What are the two basic mechanisms of mass transfer? When separating chemicals in commercial equipment, which mechanism is preferred? Why?

4. Molecular diffusion occurs by any of what four driving forces or potentials? Which one is the most common? Can molecular diffusion occur in solids, liquids, and gases?

5. What is the bulk flow effect in mass transfer?

Section 3.1:

6. What is a random-walk process?

7. Is the mass-transfer rate proportional to the area normal to the direction of mass transfer or to the volume of the mixture?

8. For a binary mixture, what factors are involved in the rate of diffusion of a component, according to Fick's law?

9. How does Fick's law of diffusion compare to Fourier's law of heat conduction?

10. What is the difference between a species diffusion velocity relative to stationary coordinates and relative to the molar average velocity of the mixture that contains the species?

11. What is meant by equimolar counterdiffusion (EMD)? In what separation operation is it closely approached?

12. For EMD, are the mole fraction profiles linear or nonlinear with distance?
13. For a binary mixture, under what conditions is the diffusivity of A in B equal to the diffusivity of B in A, and independent of composition?

14. What is meant by unimolecular diffusion (UMD)? In what separation operation is it closely approached?

15. For UMD, are the mole fraction profiles linear or nonlinear with distance?

16. Does EMD or UMD include the bulk-flow effect? How does this effect modify Fick's law?

Section 3.2:

17. When measuring molecular diffusivities, why must a correction be made for bulk flow?

18. What is the difference between a mutual diffusion coefficient and a self-diffusion coefficient?

19. Who used the kinetic theory of gases to develop a theoretical equation for estimating molecular binary diffusivities in a gas mixture at low pressures? Why is the empirical equation of Fuller, Schettler, and Giddings preferred?

20. At low pressures, what is the effect of temperature and pressure on the molecular diffusivity of a species in a binary gas mixture?

21. What is the order of magnitude of the molecular diffusivity in cm$^2$/s for a species in a binary gas mixture at low pressure?

22. Above about what pressure is a correction to the pressure effect on binary gas diffusivity necessary? What type of theory is used to make that correction?

23. In general, for a binary liquid mixture, the diffusivity of A in B and the diffusivity of B in A both depend on composition. Why is this so?
24. Which equation is useful for estimating diffusivities of solutes in aqueous solutions? On what theory is that equation based?

25. What is the order of magnitude of the molecular diffusivity in cm$^2$/s for a species in a liquid mixture? By how many orders of magnitude is diffusion in a liquid slower or faster than in a gas?

26. How is liquid diffusivity related to viscosity?

27. For what are the Vignes equations used?

28. Under what conditions must diffusion of electrolyte solutes be treated by ions?

29. By what mechanisms does diffusion occur in solids? Can Fick's law be used for diffusion in solids?

30. What is the order of magnitude of the molecular diffusivity in cm$^2$/s for a species in a solid? By how many orders of magnitude is diffusion in a solid slower or faster than in a gas?

31. By what mechanisms does diffusion occur in porous solids?

32. What is the effective diffusivity?

33. Why is diffusion in crystalline solids much slower than in amorphous solids?

34. Why is diffusion of very light gases in metals of major importance?

35. Why is diffusion of light gases in ceramics important?

36. Why is diffusion of gases and liquids in dense, nonporous polymers important?

37. What is meant by the word anisotropic? Why are diffusivities in wood dependent on direction?
Section 3.3:

38. For diffusion across the radius of a hollow cylinder, what is the proper average area for mass transfer when applying an integrated form of Fick's law?

39. For diffusion across the radius of a hollow sphere, what is the proper average area for mass transfer when applying an integrated form of Fick's law?

40. What is Fick's second law? How does it compare to Fourier's second law of heat conduction?

41. When comparing diffusion to heat conduction, is thermal conductivity or thermal diffusivity analogous to molecular diffusivity?

42. Is the rate of diffusion into a semi-infinite medium inversely proportional to time or inversely proportional to the square root of time?

43. Is the rate of diffusion into a semi-infinite medium proportional to diffusivity or proportional to the square root of diffusivity?

44. Molecular diffusion in gases, liquids, and solids ranges from slow to extremely slow. What is the best way to increase the rate of mass transfer in fluids? What is the best way to increase the rate of mass transfer in solids?

45. How does the Fourier number for mass transfer differ from the Fourier number for heat transfer?

46. For small values of the Fourier number, are the solutions for the semi-infinite slab and the infinite slab of finite thickness equivalent?

47. Under what conditions is Newman's method valid for solving problems involving slabs and cylinders of finite length?

Section 3.4:

48. In laminar flow, does mass transfer in a direction normal to the direction of flow occur by molecular diffusion, eddy diffusion, or both?
49. Are the Prandtl number and Schmidt number analogous? How?

50. What is the Peclet number for mass transfer?

51. What is the defining equation for a mass-transfer coefficient? How does it differ from Fick's law? How is it analogous to Newton's law of cooling?

52. What is the Sherwood number? How is it analogous to the Nusselt number?

53. Do velocity, temperature, and concentration boundary layers on a flat plate all build up at the same rate? If not, why not?

54. What is meant by the entry length for flow in a circular tube?

55. For mass transfer to or from the wall of a tube through which a fluid flows, is the appropriate driving force an arithmetic or log-mean average?

56. For laminar flow, can expressions for the mass-transfer coefficient be determined from theory using Fick's law?

Section 3.5:

57. What is the eddy mixing length of Prandtl?

58. What is the difference between Reynold's analogy and the Chilton-Colburn analogy? Which is more useful?

59. What is the significance of the $j$-factors for momentum, heat, and mass transfer?

60. What is the basic difference between the development of the Chilton-Colburn analogy and the Prandtl analogy?

61. For what conditions, is the Friend and Metzner analogy an improvement over the Chilton-Colburn analogy?
62. Why is the Churchill-Zajic analogy on a better theoretical basis than other analogies?

Section 3.6

63. What important result is given by the penetration theory?

64. For mass transfer across a phase interface, what is the difference between the film, penetration, and surface-renewal theories, particularly with respect to the dependence on diffusivity?

Section 3.7:

65. What is the Marangoni effect? How can it be reduced?

66. What is the two-film theory of Whitman?

67. Is equilibrium assumed to exist at the interface of two phases?

68. Why are expressions for overall mass-transfer coefficients more complex than expressions for overall heat-transfer coefficients?
Chapter 4

1. What two types of equations are used for calculations of a single equilibrium stage?

Section 4.1:

2. How do intensive and extensive variables differ?

3. What is meant by the number of degrees of freedom?

4. What is Gibbs phase rule? To what kinds of variables does it apply? Of what use is it? Can it be derived?

5. What are the limitations of the Gibbs phase rule? How can it be extended?

Section 4.2:

6. For a given binary vapor-liquid system at a fixed pressure, is the relative volatility a constant, independent of temperature?

7. Can the vapor-liquid separation of a binary mixture be made at the critical point? If not, why not?

8. Are the terms "saturated vapor" and "dew-point" synonymous? Are the terms "saturated liquid" and "bubble point" synonymous?

9. When a liquid and vapor are in physical equilibrium, why is the vapor at its dew point and the liquid at its bubble point?

10. Why are the $T$-$y$-$x$ and $y$-$x$ phase-equilibrium diagrams for a binary system at a fixed pressure the most useful such diagrams?

11. What is the $q$-line on a $y$-$x$ phase equilibrium diagram?

12. Equation (4-8) for a binary mixture relates the equilibrium vapor mole fraction of the light key to the equilibrium liquid mole fraction of the light
key for a given value of the relative volatility. What are the assumptions that lead to this equation?

Section 4.3:

13. What is the difference between a homogeneous and a heterogeneous azeotrope?

14. Is it possible to have a maximum-boiling heterogeneous azeotrope? If not, why not?

15. Why do azeotropes limit the degree of separation that can be achieved in a distillation operation?

16. What is one way that an azeotrope can be broken?

17. How does the Keyes process for making pure ethyl alcohol work?

18. What is extractive distillation?

Section 4.4:

19. What is meant by the term "flash"?

20. What is the difference between flash vaporization and partial condensation?

21. How many degrees of freedom are there for a flash?

22. What is the difference between an isothermal and an adiabatic flash?

23. Why is the isothermal-flash calculation so important?

24. Why is the isothermal-flash calculation an iterative procedure?

25. The Rachford-Rice method is frequently employed for an isothermal flash. If it cannot find a root for $V/F$ between 0 and 1, what does that mean?
26. What is the bubble-point equation? What is the dew-point equation?

27. Why is the adiabatic-flash calculation much more difficult than the isothermal-flash calculation?

Section 4.5:

28. When a binary feed is contacted with a solvent to form two equilibrium liquid phases, which is the extract and which the raffinate?

29. What is the definition of the extraction factor?

30. When is it useful for phase compositions to be expressed as mole (mass) ratios rather than mole (mass) fractions?

31. In a liquid-liquid separation system, why is it necessary that the system pressure be greater than the bubble-point pressure?

32. Why are triangular diagrams useful for liquid-liquid equilibrium calculations with a ternary system? On such a diagram, what are the miscibility boundary, plait point, and tie lines?

33. For a ternary liquid-liquid system, are the compositions of the two phases fixed at a given temperature and pressure? If not, why not?

34. For a liquid-liquid system, what is the difference between equilibrium miscibility data and tie-line (mutual equilibrium) data? Which type of data is necessary to make liquid-liquid equilibria calculations?

34. Why is the right-triangle diagram easier to construct and read than an equilateral-triangle diagram? What is, perhaps, the only advantage of the latter diagram?

35. What is the difference between a distribution diagram and a Jaencke diagram?

36. What is a mixing point on a triangular diagram?

37. What is solutropy?
Section 4.6:

38. Why are multicomponent liquid-liquid equilibrium calculations difficult?

Section 4.7:

39. What separation operations involve solid-liquid phase equilibrium?

40. What are the conditions for an ideal, equilibrium leaching stage?

41. In leaching, why does the underflow contain liquid?

42. In leaching, when the overflow and underflow are in equilibrium, how are the respective solute concentrations related?

43. In leaching, how is the ratio of solids to liquid in the underflow determined?

44. In crystallization, what is a eutectic? What is mother liquor? What are hydrates?

45. What is the difference between adsorbent and adsorbate?

46. What is an adsorption isotherm? Does it have anything to do with phase equilibrium?

47. In adsorption, why are adsorbents having a microporous structure desirable?

48. What is the Freundlich equation?
Section 4.8:

49. Can a component in a gas mixture at a temperature that is above its critical temperature dissolve in a liquid?

50. Can Raoult's law be applied to a supercritical component? If not, what law can be used?

Section 4.9:

51. What is sublimation? What is desublimation?

52. Under what conditions does desublimation occur?

53. Does a solid have a vapor pressure?

54. Can components of a gas mixture adsorb to different extents on a solid?

Section 4.10:

55. What is the maximum number of phases that can exist at physical equilibrium for a given number of components?

56. In general, calculations of vapor-liquid-liquid equilibria are complicated. Under what conditions can a simple method of solution be applied?

57. In a rigorous vapor-liquid-liquid equilibrium calculation (so-called three-phase flash), is it necessary to consider all possible phase conditions, i.e. all liquid, all vapor, vapor-liquid, liquid-liquid, as well as vapor-liquid-liquid?

58. What is the secondary dew point? Is there also a secondary bubble point?
Chapter 5

1. What is a separation cascade? What is a hybrid system?

Section 5.1:

2. What is the difference between a countercurrent and a crosscurrent cascade?

3. What is the limitation of a single-section cascade? Does a two-section cascade overcome this limitation?

4. What is an interlinked system of stages?

Section 5.2:

5. What is a tridiagonal matrix?

6. What method is used to solve a tridiagonal-matrix equation?

7. What is the washing factor?

8. What is the difference between a leaching and a washing stage?

Section 5.3:

9. Does a cocurrent cascade have any merit for liquid-liquid extraction? If not, why not?

10. Which is more efficient, a crosscurrent cascade or a countercurrent cascade?

11. Can a crosscurrent cascade accomplish complete extraction with an infinite number of stages?

12. Under what conditions can a countercurrent cascade achieve complete extraction?
Section 5.4:

13. Why is a two-section cascade used for distillation?

14. What is a group method of calculation?

15. What is the Kremser method? To what type of separation operations is it applicable? What are the major assumptions of the method?

16. What is an absorption factor? What is a stripping factor?

17. Why is a stripper frequently coupled with an absorber?

18. In distillation, what is meant by reflux, boilup, rectification section, and stripping section?

Section 5.5:

19. Why does a single membrane stage sometimes consist of a set of membrane modules in parallel?

20. Under what conditions is a membrane cascade of multiple stages in series necessary?

21. Why are membrane cascades with recycle sometimes considered?

Section 5.6:

22. Why are hybrid systems often considered?

23. State five hybrid systems that use different separation methods.

24. Give an example of a hybrid system that involves recycle.

25. Explain how a distillation-crystallization hybrid system works for a binary mixture that exhibits both an azeotrope and a eutectic.
Section 5.7:

26. When solving a separation problem, are the number and kind of specifications obvious? If not, how can the required number of specifications be determined?

27. What is the number of degrees of freedom for an $N$-stage countercurrent cascade of non-adiabatic equilibrium stages.

28. Can the degrees of freedom be determined for a hybrid system? If so, what is the easiest way to do it?
Chapter 6

1. In absorption, what is a solute?

2. Can absorption be accompanied by a temperature change? Why?

3. What is the difference between physical absorption and chemical (reactive) absorption?

4. What is the difference between an equilibrium-based and a rate-based calculation procedure?

Section 6.1:

5. What is a trayed tower? What is a packed column?

6. What is the difference between entrainment and occlusion?

7. What are the three most common types of openings in trays for the passage of vapor? Which of the three is rarely specified for new installations?

8. In a trayed tower, what are weirs and downcomers?

9. In a trayed tower, what is meant by flooding and weeping?

10. Why are liquid distributors and redistributors necessary in a packed column, but not in a trayed tower?

11. What is the difference between random and structured packings?

12. What are the four generations of column packings?

13. What are the advantages of the more-expensive structured packings over the random packings?

14. For what conditions is a packed column favored over a trayed tower?

15. Why do most retrofits involve the replacement of trays with packing?
Section 6.2:

16. What factors must be considered when designing an absorber or a stripper?

17. What are the characteristics for an ideal absorbent? What are the characteristics of an ideal stripping agent?

18. In general, why should the operating pressure be high and the operating temperature be low for an absorber, and the opposite for a stripper?

19. For a given recovery of a key component in an absorber or stripper, does a minimum absorbent or stripping agent flow rate exist for a tower or column with an infinite number of equilibrium stages?

Section 6.3:

20. When using a graphical method for determining the number of equilibrium stages required for an absorber or stripper, when is it advisable to express solute concentrations in mole ratios, rather than mole fractions?

21. What is an operating-line equation?

22. What is the difference between an operating line and an equilibrium curve?

23. On a Y-X plot for an absorber, is the operating line above or below the equilibrium curve? Explain.

24. On a Y-X plot for a stripper, is the operating line above or below the equilibrium curve? Explain.

25. What is a reasonable value for the optimal absorption factor when designing an absorber? Does that same value apply to the optimal stripping factor when designing a stripper?
26. When stepping off stages on a $Y$-$X$ plot for an absorber or a stripper, does the process start and stop with the operating line or the equilibrium curve?

Section 6.4:

27. When should the use of an algebraic method, rather than a graphical method, be considered for determining stage requirements for an absorber or stripper?

28. At near ambient pressure, what four methods should be considered for estimating the $K$-value of a solute?

29. What is a VOC?

Section 6.5:

30. Is stage efficiency usually based on heat transfer, mass transfer, or a combination of the two?

31. What is the definition of Lewis for the overall stage efficiency?

32. What are the main factors that influence the overall stage efficiency?

33. What are the four methods for predicting stage efficiency?

34. In general, do absorbers or strippers have the higher stage efficiency? Why?

35. What is the advantage of the O'Connell empirical correlation over the Drickamer and Bradford empirical correlation?

36. Why do longer liquid-flow paths give higher stage efficiencies?

37. Why do large diameter towers often use multiple-pass trays?

38. What are the assumptions in the Murphree vapor (tray) efficiency?
39. What is the difference between the Murphree tray and point efficiencies?

40. Under what conditions is the Murphree vapor tray efficiency equal to the Lewis overall stage efficiency?

41. What kind of a laboratory column is used to obtain data suitable for scale-up to commercial columns?

Section 6.6:

42. What are the four conditions for ideal stable operation of a trayed column?

43. What is the difference between downcomer flooding and entrainment flooding? Which is the more common type of flooding?

44. Why does the flooding velocity depend on the tray spacing?

45. Why does foaming tendency affect the flooding velocity?

46. Is surface tension a major factor in determining flooding velocity?

47. What are the major factors that determine tower diameter?

48. What is meant by turndown ratio? What type of tray has the best turndown ratio? Which, the worst?

49. How do the new high-capacity trays differ from conventional trays?

50. What are the three contributing factors to the vapor pressure drop across a tray?

51. Does vapor velocity affect both vapor-phase and liquid-phase mass-transfer coefficients?

52. Can the Chan-Fair method be used to predict both vapor-phase and liquid-phase mass-transfer coefficients?
53. Why does the vapor-phase mass-transfer coefficient decrease as the flooding velocity is approached?

54. For what type of tray is weeping potential the most serious?

55. Can the rate of liquid entrainment be estimated? If so, how?

56. Why is the clear liquid head in the downcomer greater than the vapor pressure drop per tray expressed as a liquid head?

Section 6.7:

57. What is the HETP? Does it have a theoretical basis? If not, why is it so widely used?

58. What are typical values of HETP for random packings and for structured packings?

59. Under what conditions is the HETP equal to the HTU, and the number of theoretical stages equal to the NTU?

60. Why are there so many different kinds of mass-transfer coefficients? How can they be distinguished?

Section 6.8:

61. What is the loading point in a packed column?

62. What is the flooding point in a packed column?

63. At low superficial gas velocities, does the holdup depend on gas velocity or just liquid rate?

64. For operation below the loading point, what is the relationship between the pressure drop for vapor flow, but without liquid flow, and that for vapor flow with liquid flow?
65. What is the loading region? Is it best to operate a packed column in that region or in the pre-loading region?

66. Can a packed column be operated efficiently without achieving complete wetting of the packing with liquid?

67. What is the difference between the kinetic energy ratio of Sherwood et al. and the $F$-factor?

68. What is an approximate value of the pressure drop in a packed column when flooding is closely approached?

69. Are liquid density and viscosity important in determining flooding velocity in a packed column?

70. What is the most widely used correlation for estimating dry-bed pressure drop?

71. How does the HETP vary with the $F$-factor?

72. Which has the greater influence: (1) the gas velocity on the liquid-phase volumetric mass-transfer coefficient, or (2) the liquid velocity on the gas-phase volumetric mass-transfer coefficient?

Section 6.9:

73. When the solute concentration is moderate to high, instead of dilute, why are calculations for packed columns much more difficult?
Chapter 7

1. What are the three requirements of distillation?

2. How does distillation differ from absorption and stripping?

3. What is the most widely used industrial method for separating a liquid mixture?

4. What equipment is included in a typical distillation operation?

5. Why is distillation considered to be a mature separation method?

Section 7.1:

6. What are the factors that influence the design of distillation column?

7. What determines the operating pressure of a distillation column?

8. Under what conditions does a distillation column have to operate under vacuum?

9. In the design of a distillation column, why is there a trade-off between the number of stages and the reflux ratio?

Section 7.2:

10. Why are distillation columns arranged for countercurrent flow of liquid and vapor?

11. In a binary mixture, which component is the light key? Is the light key found mainly in the distillate or the bottoms?

12. What is the goal of binary distillation? Does azeotrope formation prevent the attainment of the goal?

13. When the two components of a binary mixture follow Raoult's and Dalton's laws, what is the relative volatility equal to?
14. If the relative volatility of a binary mixture is constant at a given pressure, what equation can be used to compute the vapor composition that is in equilibrium with a liquid composition?

15. Why is the McCabe-Thiele graphical method useful in this era of more rigorous computer-aided algebraic methods?

16. What does the McCabe-Thiele method assume about the column pressure?

17. What can the McCabe-Thiele method determine?

18. Under what conditions does the McCabe-Thiele assumption of constant molar overflow hold?

19. On the McCabe-Thiele graph, which component is plotted, the LK or the HK?

20. What is the operating-line equation for the rectifying section? How is it derived? Does it have anything to do with equilibrium?

21. In the McCabe-Thiele method, between which two lines is the staircase constructed?

22. What is meant by the reflux ratio?

23. In the rectification section, how is \( L/V \) related to \( R \)?

24. What is the operating-line equation for the stripping section? How is it derived?

25. What is meant by the boilup ratio? How is it related to \( \bar{L}/\bar{V} \)?

26. Which has the largest slope, the rectifying section operating line or the stripping section operating line? Why?

27. Are the reflux ratio and boilup ratio related? If so, how are they influenced by the feed condition?

28. How is \( q \) related to the feed condition?
29. What are the five possible feed conditions?

30. What is the equation for the $q$-line (also called feed line)? How is it derived?

31. Under what conditions does the $q$-line have a negative slope?

32. Do the $q$-line and the two operating lines intersect at a point?

33. In the McCabe-Thiele method, are the stages stepped off from the top down or the bottom up? In either case, when is it best, during the stepping, to switch from one operating line to the other? Why?

34. What are the three limiting conditions for the McCabe-Thiele method?

35. When determining the minimum number of stages, Why are the two operating lines on the 45° line?

36. What is the reflux ratio equal to for the minimum number of stages?

37. Can a column be operated at total reflux? How?

38. Does the minimum number of stages depend upon the feed condition?

39. For operation at total reflux, is there a column feed, distillate, and bottoms? If not, why not?

40. How many stages are necessary for operation at minimum reflux ratio?

41. Can a distillation be operated at minimum reflux ratio?

42. What is meant by a pinch point? Is it always located at the feed stage?

43. Is there a minimum reflux ratio for a perfect binary separation?

44. Is the minimum reflux ratio sensitive to the degree of separation of the two key components when a reasonably sharp split is made?

45. How is a reasonable column operating pressure established?
46. What are the three types of condensers? Which is the most common? Which one is not an equilibrium stage? Which one is equivalent to an equilibrium stage?

47. What is meant by subcooled reflux?

48. How does subcooled reflux affect the amount of reflux inside the column?

49. What are the three main types of reboilers? Is each equivalent to a theoretical stage?

50. How are condenser and reboiler heat duties computed?

51. Is it worthwhile to preheat the feed to a distillation column?

52. What is the range of the optimal ratio of reflux to minimum reflux?

53. Are techniques available to determine large numbers of stages by the McCabe-Thiele method?

54. Is equilibrium always achieved on the tray of a distillation column?

55. How is the Murphree vapor efficiency defined for a tray in a distillation column?

56. How is the McCabe-Thiele method modified to handle multiple feeds, side streams, and the use of stripping steam in place of the reboiler?

Section 7.3:

57. Why is the stage efficiency in distillation higher than in absorption?

58. What data are needed to calculate Murphree tray efficiencies for an operating distillation column?

59. What is the difference between the Drickamer-Bradford and O'Connell empirical correlations for overall plate efficiency?
60. What kind of a small laboratory column is useful for obtaining plate efficiency data?

Section 7.4:

61. What is the basis for determining the diameter and length or height of a reflux drum?

62. What are the two rate-based methods for determining the packed height of a distillation column? Do both methods have a sound theoretical basis? If not, which one does?

63. How is the HETP method used for distillation? Are mass-transfer coefficients needed? If not, why not?

64. Are mass-transfer coefficients needed for the HTU method? How are they obtained?

Section 7.5:

65. What is the difference between the McCabe-Thiele method and the Ponchon-Savarit method?

66. Is it easy or difficult to construct an enthalpy-concentration diagram for a binary mixture.
Chapter 8

1. In a ternary extraction system, what are the solute, solvent, and carrier?

2. When liquid-liquid extraction is used, are other separation operations needed? Why?

3. Is liquid-liquid extraction a reasonably mature separation operation? In this respect, how does it compare to distillation?

4. Is thermodynamic data for liquid-liquid equilibria a major problem for extraction?

5. Under what conditions is extraction preferred to distillation?

6. What is the key to the development of an effective extraction process?

7. What are the important characteristics of a good solvent?

Section 8.1:

8. Compared to distillation, is there a wider diversity of equipment for liquid-liquid extraction? Why?

9. Can equipment used for distillation be used for extraction? Is it always effective? If not, what is lacking?

10. What is meant by the dispersed phase and the continuous phase?

11. Can mixer-settler units be connected together to form a continuous, multistage, countercurrent extraction device?

12. Can a mixer-settler unit be designed to closely approach phase equilibrium?

13. What is a major problem in designing a gravity settler?

14. What are the most common types of impellers used in mixers for extraction?
15. What is the major limitation of a spray column for extraction?

16. When using a packed column for extraction, should the packing material be selected so that it is preferentially wetted by the continuous or the dispersed phase? Why?

17. When using a plate column for extraction, when must upcomers be used in place of downcomers?

18. Under what conditions is mechanically assisted agitation necessary in an extraction column?

19. What are the various methods for mechanically inducing agitation in a column?

20. How is agitation induced in the following types of column extractors: (1) Scheibel, (2) Oldshue-Rushton, (3) RDC, (4) ARD, (5) Kuhni, and (6) RPC?

21. How does the Graesser extractor work?

22. Which commercial extraction column has the highest throughput per cross-sectional area?

23. Which commercial extraction columns can be fabricated in the largest diameters?

24. What are the advantages and disadvantages of mixer-settler extractors?

25. What are the advantages and disadvantages of continuous, counterflow, mechanically assisted extractors?

Section 8.2:

26. What is the difference between a single-section and a two-section extractor?
27. Why are two-section extractors used? Why are two solvents sometimes used?

28. What factors influence extraction?

29. What are the characteristics of an ideal solvent?

30. What is the relative selectivity?

31. When should an organic solvent be selected? When should an aqueous solvent be selected?

32. What is the difference between a Type I and Type II ternary system? Can a system transition from one type to the other by changing the temperature? Why?

33. What is the significance of Figure 8.11?

34. Does pressure have any significant effect on liquid-liquid equilibrium?

35. At what temperature do most extractors operate?

36. Why is some laboratory or pilot-plant work necessary before designing an extraction unit?

37. When the minimum amount of solvent is used, how many equilibrium stages are needed?

Section 8.3:

38. What are the assumptions for the Hunter-Nash method?

39. What is meant by the mixing point? For a multistage extractor, is the mixing point on a triangular diagram the same for the feeds and the products?

40. What is meant by solutropy?
41. Can triangular diagrams be constructed for compositions in mole fractions or mass fractions?

42. What is the difference between tie lines, operating lines, and operating points?

43. What are the best ways to interpolate tie lines?

44. What happens if more than the maximum solvent rate is used?

45. What happens if less than the minimum solvent rate is used?

46. In what respect is the Hunter-Nash construction for determining stage requirements on the triangular diagram similar to the staircase construction of the McCabe-Thiele diagram for distillation?

47. Are any new principles involved in applying the Hunter-Nash method to a right-triangular diagram rather than an equilateral-triangular diagram?

48. When should an auxiliary distribution curve be used with a triangular diagram?

49. What is the Varteressian-Fenske technique? How is it used?

50. What are extract and raffinate reflux? Which one is of little value? Why?

**Section 8.4:**

51. For what type of ternary system is the Maloney-Schubert method used?

52. How is the Janecke diagram analogous to the enthalpy-concentration diagram?

**Section 8.5:**

53. What are the main considerations in selecting between mixer-settler units and columns with mechanically assisted agitation?
54. What is the typical range of residence time for approaching equilibrium in an agitated mixer when the liquid-phase viscosities are less than 5 cP.

55. What is a common type of impeller used in mixer-settler units?

56. What is vortexing? Under what conditions does it occur? Should it be avoided?

57. Can a power consumption curve for the agitation of a single liquid phase without vortexing be used to estimate the power consumption for the agitation of two liquid phases?

58. When continuously bringing together two liquid phases in an agitated vessel, are the residence times of the two phases in the vessel necessarily the same? If not, are there any conditions where they would be the same?

59. For an agitated vessel, is it always possible to predict which phase will be the dispersed phase?

60. For the complete dispersion of one liquid phase in another, how can the minimum impeller rotation rate be estimated?

61. What is the Murphree dispersed-phase efficiency? How is it related to the overall volumetric mass-transfer coefficient?

62. There are many definitions of mean droplet or particle diameter. Which definition is most useful for extraction applications?

63. What is the Weber number? Why is it important in extraction?

64. Why is liquid-liquid mass transfer complex in agitated systems?

65. What are Marangoni effects? How do they influence mass transfer?

66. In the absence of motion or Marangoni effects, what are the Sherwood numbers for mass transfer within and without a spherical droplet suspended in another liquid?
67. For multicompartment columns, which types have the most favorable HETS values?

68. What is meant by the slip velocity?

69. For extraction, what is the best way to determine an HETS value? If the value is determined for a small laboratory or pilot-plant column, can the HETS be used to size a large commercial column? If so, how?

70. What is axial dispersion? Is it to be avoided?

71. What causes axial dispersion? Is it more significant in the continuous or dispersed phase?
Chapter 9

1. Rigorous computer-based methods for multicomponent distillation are readily available. Why then is the FUG approximate method still useful and widely applied for distillation?

Section 9.1:

2. What does the acronym FUG stand for?

3. When calculating multicomponent distillation, why is it best to list the components in order of decreasing volatility? In such a list, do the two key components have to be adjacent?

4. When making a preliminary estimate of the distribution of feed components between distillate and bottoms, when is it reasonable to assume perfect splits for nonkey components?

5. How are feed conditions established at the feed location of a distillation column?

6. What does the Fenske equation compute? Be precise! Is it a theoretical or empirical equation? Is it an exact equation? If not, what assumptions are made in its derivation?

7. Does the Fenske equation assume constant molar overflow as in the McCabe-Thiele method?

8. For what conditions should the Fenske equation be used with caution?

9. Is use of the Fenske equation restricted to the two key components? If not, what else can the Fenske equation be used for besides the estimation of the minimum number of equilibrium stages, corresponding to total reflux?

10. Can a distillation column be operated at total reflux?

11. Can a distillation column be operated under conditions of minimum reflux? If not, why not?
12. What is a pinch point or region? For multicomponent distillation, under what conditions is the pinch point located at the feed location? What conditions cause the pinch point to migrate away from the feed location?

13. What is the difference between a Class 1 and a Class 2 separation?

14. Which Underwood equation is used to compute the minimum reflux of a Class 1 separation?

15. Why is the Class 1 Underwood equation useful even if the separation is Class 2?

16. What is internal reflux? How does it differ from external reflux? Does the Underwood equation compute internal or external reflux? How can one be determined from the other?

17. What makes the derivation of Underwood's minimum reflux equation for Class 2 separations difficult?

18. What two assumptions are necessary to derive Underwood's equation for a Class 2 separation?

19. What Underwood equations must be solved for a Class 2 separation? Does the method of solution depend on whether a nonkey component distributes or not?

20. For a Class 2 separation, under what condition might the Underwood method give an unreliable estimate of minimum reflux?

21. What is the optimal range of values for $R/\text{min } R$?

22. Is the Gilliland correlation for actual stages and reflux theoretical or empirical? If the latter, how was the correlation developed?

23. What key parameter is missing in the Gilliland correlation?

24. What optimal ratio of $N/\text{min } N$ does the Gilliland correlation predict?

25. When can a serious problem arise with the Gilliland correlation?
26. How can the Fenske equation be used to determine the optimal ratio of rectifying to stripping stages? Is it accurate? If not, what alternative equation is preferred? Is the alternative equation always reliable?

27. What is the best method for estimating the distribution of nonkey components at the actual (operating) reflux?

Section 9.2:

28. Is the Kremser method a group method? What is meant by a group method? Can it be applied to liquid-liquid extraction?
Chapter 10

1. Why are rigorous solution procedures difficult and tedious for multicomponent, multistage, separation operations?

Section 10.1:

2. What are the assumptions for the theoretical model of an equilibrium stage? What composition variables are used for the two phases? What types of equations are written? Why are they called the MESH equations?

3. In the equilibrium-stage model, can each stage have a feed, a vapor sidestream, and/or a liquid sidestream? How many independent equations apply to each stage for \( C \) components?

4. In the equilibrium-stage model equations, are \( K \)-values and enthalpies counted as variables? Are the equations used to compute these properties counted as equations?

5. For a cascade of \( N \) countercurrent equilibrium stages, what is the number of variables, number of equations, and number of degrees of freedom? What are typical specifications, and what are the typical computed variables? Why is it necessary to specify the number of equilibrium stages and the locations of all sidestream withdrawals and heat exchangers?

Section 10.2:

6. Early attempts to solve the MESH equations were the Lewis-Matheson and Thiele-Geddes methods. Why are they not favored for computer calculations?

7. What are the four methods most widely used to solve the MESH equations?

8. How do equation-tearing and Newton-Raphson procedures differ?
Section 10.3:

9. What is a tridiagonal-matrix (TDM) equation? How is it developed from the MESH equations? In the matrix equation, what are the variables and what are the tear variables? What is a tear variable? Is there one TDM equation for each component? If so, can each equation be solved independently of the others?

10. What is the Thomas algorithm?

11. Why is the Wang-Henke method called the Bubble-Point (BP) method? For what types of problems does it work? Are initial estimates of the tear variables required? If so, how is that accomplished?

12. What is meant by normalization of a set of variables?

13. In the BP method, which of the MESH equations is used to compute a new set (i.e. update) of total molar vapor flow rates leaving each stage?

14. What criterion is used to determine convergence of the BP method?

15. Is convergence of the BP method sensitive to the initial guesses for the tear variables?

16. What types of plots are useful for displaying the results of the BP method?

17. Why is the modified McCabe-Thiele diagram of Fig. 10.14 useful?

18. Does the Sum-Rates (SR) method use tridiagonal-matrix equations? How does the SR method differ from the BP method? For what types of problems is the SR method preferred over the BP method? What are the tear variables in the SR method?

19. Why does the set of stagewise enthalpy balances in the SR method have to be solved simultaneously by the Newton-Raphson method for a new set of temperatures?

20. What is the criterion for convergence of the SR method?
21. Are stagewise enthalpy balances important when solving multicomponent, multistage, liquid-liquid extraction problems? If not, why not? What is the most difficult aspect of the isothermal sum-rates method?

Section 10.4:

22. What limitations of the BP and SR methods are overcome by the Newton-Raphson (NR) methods? How do the NR methods differ from the BP and SR methods?

23. How do the Goldstein-Stanfield and Naphtali-Sandholm NR procedures differ?

24. Why does the NR procedure of Naphtali and Sandholm use, as composition variables, the component flow rates rather than mole fractions?

25. In the Naphtali-Sandholm method, are the equations grouped by stage or type? Under what conditions is it preferable to group the equations by type?

26. What is the difference between a tridiagonal-matrix (TDM) equation and a block-tridiagonal-matrix (BTDM) equation? How do the algorithms for solving these two types of equations differ?

27. In the BP and SR methods, the TDM equations are linear in the variables. Is the BTDM equation of the Naphtali-Sandholm method linear? If not, how is it solved?

28. What is a Jacobian matrix? How is the Jacobian formulated?

29. What is the convergence criterion for the Naphtali-Sandholm method?

30. Is it always advisable to apply the full correction at each iteration of the Naphtali-Sandholm method? If not, how is the fraction of the correction to be applied best determined?

31. If the correction causes some variables to become negative, what should be done?
Section 10.5:

32. What types of calculations consume the most time in the BP, SR, and NR methods? How does the Inside-out method reduce this time?

33. How do the iteration variables in the Inside-out method differ from those in the NR methods?

34. Why is the Inside-out method sometimes referred to as a two-tier method?

35. To what types of problems can current implementations of the Inside-out methods be applied?

36. Would it be expected that for a given problem, the NR and Inside-out methods would converge to the same result?
Chapter 11

1. What is meant by enhanced distillation? When should it be considered?

2. What is the difference between extractive distillation and azeotropic distillation?

3. What is the difference between homogeneous and heterogeneous azeotropic distillation?

4. What are the two reasons for conducting reactive distillation?

5. Why do enhanced distillation calculations frequently fail?

Section 11.1:

6. Can vapor-liquid phase equilibria for a ternary mixture at a fixed pressure be represented on a triangular diagram? If so, why is it rarely done?

7. What do the curves on the triangular diagrams of Fig. 11.3 represent?

8. What is the direct sequence of distillation columns? What is the indirect sequence? Why would you expect the direct sequence to be favored?

9. What is a distillation boundary? Why is it important?

10. To what type of a distillation does a residue curve apply? What is a residue-curve map?

11. Is a residue curve computed from an algebraic or a differential equation? Does a residue curve follow the composition of the distillate or the residue?

12. Residue curves involve nodes. What is the difference between a stable and an unstable node? What is a saddle?

13. Can a residue-curve map be quickly approximated? How?

14. What is the number of possible types of curve maps?
15. What is a distillation-curve map? How does it differ from a residue-curve map?

16. Is a distillation curve computed from algebraic or differential equations? Under what conditions is a distillation curve identical to a residue curve?

17. Why do the arrows on a distillation-curve map point in directions opposite to a residue-curve map?

18. What is a region of feasible product compositions? How is it determined? Why is it important?

19. Under what conditions can a distillation boundary be crossed by a material-balance line?

Section 11.2:

20. Under what conditions should extractive distillation be considered?

21. What are the characteristics of a desirable solvent for extractive distillation?

22. Can a binary azeotrope be separated by extractive distillation followed by ordinary distillation? Sketch a process-flow diagram showing how this can be done?

23. In extractive distillation, why is a large concentration of solvent required in the liquid phase? Why doesn't the solvent enter the column at the top tray?

Section 11.3:

24. Under what conditions should salt distillation be considered? What is the effect of the salt? What are potential problems that may accompany salt distillation?

25. What is the difference between salting in and salting out?
Section 11.4:

26. Under what conditions should pressure-swing distillation be considered for the separation of an azeotrope?

27. Why are two columns required for pressure-swing distillation?

28. Why is the recycle ratio an important factor in the design of a pressure-swing distillation system?

Section 11.5:

29. In azeotropic distillation, what is the entrainer?

30. In homogeneous azeotropic distillation, why are there so many possibilities to consider, as shown in Fig. 11.26?

31. What makes the application of a sequence involving just homogeneous azeotropic distillation and ordinary distillation difficult?

Section 11.6:

32. Why is heterogeneous azeotropic distillation a more feasible technique than homogeneous azeotropic distillation?

33. What is a decanter? How is it used in heterogeneous azeotropic distillation?

34. Should the formation of two liquid phases (phase splitting) be avoided in the top trays of a heterogeneous azeotropic distillation column?

35. What is the most common sequence for the use of heterogeneous azeotropic distillation?

36. What is meant by multiplicity? What kinds of multiplicity are there?
37. Why is it important to obtain all multiple solutions when they exist?

Section 11.7:

38. In reactive distillation, does the reaction preferably take place in the vapor or liquid phase? Can a homogeneous or solid catalyst be used?

39. What have been the two major applications of reactive distillation?

40. When large liquid holdups are required to provide the necessary residence time for a reaction, what type of trays are preferred?

41. Can multiplicity occur in reactive distillation? If so, give an example.

Section 11.8:

42. What is the supercritical-fluid region?

43. What happens to the solvent power of a compressed gas as it passes through the critical region? What happens to physical properties in the critical region?

44. What are the key characteristics of a desirable solvent for SCE?

45. Why is carbon dioxide frequently a desirable solvent for SCE?

46. What techniques can be used to recover CO$_2$ when it is used as a solvent in SCE?

47. Is phase equilibrium difficult to predict for SCE? If so, what prediction methods are preferred?
Chapter 12

1. For binary distillation, what assumption did Smoker add to the McCabe-Thiele assumptions to obtain an algebraic solution?

2. What assumptions did Murphree make in the development of his tray-efficiency equations?

3. For which situations does the Murphree efficiency appear to be adequate? What are its deficiencies?

4. What unusual phenomena did Toor find for diffusion in a ternary mixture? Is a theory available to predict these phenomena?

5. Who developed the first practical computer program for vapor-liquid separations using a transport (rate-based) model?

Section 12.1:

6. In the rate-based model, is the assumption of phase equilibrium used anywhere? If so, where? Is it justified?

7. The rate-based model requires component mass-transfer coefficients, interfacial areas, and heat-transfer coefficients. How are the latter obtained?

Section 12.2:

8. What are component-coupling effects in mass-transfer rate equations?

9. Does the rate-based model account for the bulk-flow effect in mass transfer?

Section 12.3:

10. Can the rate-based model be applied to packed columns?

11. What is the Lewis number? What is it used for?
Section 12.4:

12. Are tray flow patterns important in the rate-based model? What are the ideal flow-pattern models?

13. What is a rate-based multicell model?

Section 12.5:

14. What method is used to solve the set of nonlinear equations for the rate-based model?

15. Do the ChemSep and RATEFRAC programs provide flexible specifications? Give examples.
Chapter 13

1. How does batch distillation differ from continuous distillation?

2. When should the use of batch distillation be considered?

Section 13.1:

3. What is differential (Rayleigh) distillation?

4. Is differential distillation modeled by an algebraic or differential equation?

5. For what kinds of mixtures is differential distillation adequate?

6. What assumptions are made to derive (13-5)?

Section 13.2:

7. What is a batch rectifier?

8. What assumption is necessary to permit the application of the McCabe-Thiele diagram to a batch rectifier operating at a constant reflux ratio?

9. What is the easy way to determine the average composition of the distillate from a batch rectifier?

Section 13.3:

10. Which is easier to implement: (1) the constant reflux policy, (2) the constant distillate composition policy, or (3) the optimal control policy? Why?

11. Is the McCabe-Thiele method easily applied to a batch rectifier operating at a constant distillate composition? Why?
Section 13.4:

12. What is a batch stripper?

13. Can a batch rectifier and a batch stripper be combined? If so, what advantage is gained?

Section 13.5:

14. What effects does liquid holdup have on batch rectification?

Section 13.6:

15. What method developed for continuous distillation is used by shortcut methods for multicomponent batch rectification?

16. Do the shortcut methods account for liquid holdup?

Section 13.7:

17. What are the assumptions of the rigorous model of Distefano?

18. Why is the Distefano model referred to as a differential-algebraic system?

19. What is the difference between truncation error and stability?

20. How does the explicit Euler method differ from the implicit method?

21. What is stiffness and how does it arise. What criterion can be used to determine the degree of stiffness, if any?

22. What is meant by a quasi-steady-state procedure? How is it applied to the rigorous model?

23. In the development of campaigns for batch distillation, what is done with intermediate (slop) cuts?
Section 13.8:

24. If the feed to a batch rectification column contains four components and it is desired to obtain four reasonably pure products, how many slop cuts may be needed? What is done with the slop cuts?

25. What are the common objectives of optimal control of a batch distillation, as cited by Diwekar.

26. What is varied to achieve optimal control?

27. What are the most commonly used mathematical methods for achieving an optimal control policy for batch distillation?

28. What famous mathematicians worked on the optimal path for the Brachistrone problem? What type of curve is the optimal path?
Chapter 14

1. What is a membrane and how does it effect the separation of a mixture? Can the feed mixture be either liquid or gas?

2. What are the two products from a membrane separation called? What is a sweep?

3. What kinds of materials are membranes made from? Can a membrane be porous or nonporous?

4. How does a membrane separation differ from distillation?

5. What were the major breakthroughs that led to widespread use of membrane separations following World War II?

6. What are the eight most common membrane separation processes? Give an industrial application of each one.

Section 14.1:

7. Is it true that almost all industrial membrane processes use natural or synthetic polymers? Give an example of each kind of polymer.

8. What is the difference between a thermoplastic and a thermosetting polymer? What is the difference between a glassy and a crystalline polymer? What does amorphous mean?

9. What is the glass-transition temperature? To what kind of polymer does it apply? To what kind of a polymer does the melting point apply? What is a rubbery polymer? Give one example each of glassy, crystalline, and rubbery polymers.

10. What is the basic equation for computing the rate of mass transfer through a membrane? Explain each of the four factors in the equation and how they can be exploited to obtain necessary high rates of mass transfer.

11. What is the difference between the permeability and the permeance? How are they analogous to the diffusivity and the mass-transfer coefficient?
12. What is the difference between an asymmetric membrane and a composite membrane? Under what conditions does a thin polymer membrane need a support layer? Why is caulking sometimes needed? What is a permselective layer?

Section 14.2:

13. For a membrane separation, is it usually possible to achieve both a high permeability and a large separation factor?

14. What are the four most common membrane shapes? Which two are the most widely used? Why?

15. What are the six most common membrane modules? Which three are most widely used?

16. Under what conditions would a hollow-fiber module be a poor choice?

Section 14.3:

17. What are the three mechanisms for mass transfer through a porous membrane? Which two are the best for making a separation? Why?

18. What is the mechanism for mass transfer through a dense (nonporous) membrane? Why is it called solution-diffusion? Does this mechanism work if the polymer is completely crystalline? Explain.

19. For bulk flow through a porous membrane, is the flow almost always laminar or turbulent? Explain.

20. What equation can be used to calculate the rate of bulk flow through a porous membrane?

21. What mass-transfer law can be applied to liquid diffusion through a membrane? How must this law be modified when the size of the diffusing molecules is of the order of the pore diameter? What is Knudsen diffusion?
22. How do the solution-diffusion equations differ for liquid transport and gas transport? How is Henry's law used for solution-diffusion for gas transport? Why are the film resistances to mass transfer on either side of the membrane often negligible?

23. For the solution-diffusion mechanism, how can the permeability be computed from the membrane diffusivity and the membrane solubility of the species?

24. How is the separation factor defined for a membrane separation? How does the definition differ from the relative volatility for distillation?

25. What assumption is used to obtain the definition of the ideal separation factor for a membrane gas separation?

26. When computing gas permeation, why is the assumption of perfect mixing on each side of the membrane often made?

27. What are the four idealized flow patterns in membrane modules? Which is the most effective? Which is the most difficult to calculate?

28. What is meant by the cut, \( q \)? What is the significance of a cut of one?

29. Why are membrane cascades sometimes used? What are the most common cascades?

30. What is concentration polarization? When should it be taken into account?

Section 14.4:

31. What is dialysis? What are some of its major applications?

32. What is electrodialysis? What is it used for?

Section 14.5:

33. What is osmosis? Can it be used to separate a liquid mixture?
34. What is reverse osmosis? How is it used to purify water? What is the preferred membrane material?

35. What is the osmotic pressure? Is it a thermodynamic quantity? How is it measured and calculated?

36. What is the Merten equation for mass transfer of a solvent through a membrane that is used for reverse osmosis?

37. Why does water have to be pumped to a high pressure in order to purify it by reverse osmosis?

38. What is meant by salt passage? How is it used in calculating reverse osmosis?

Section 14.6:

39. Can a near perfect separation be made with gas permeation? If not, why not?

40. What are the major applications of gas permeation?

Section 14.7:

41. What is pervaporation?

42. What are the major applications of pervaporation?

43. What is the mass-transfer equation for pervaporation?

Section 14.8:

44. How do microfiltration and ultrafiltration differ from reverse osmosis with respect to pore size, pressure drop, and the nature of the permeate?

45. What is meant by cutoff in ultrafiltration?
46. What is meant by rejection, $\sigma$, in ultrafiltration?

47. In ultrafiltration, what factors does the solvent flux depend upon?

48. Why can concentration polarization be an important effect in ultrafiltration?

49. What are the four common configurations for ultrafiltration?

50. What is continuous, feed-and-bleed ultrafiltration? What are its limitations?

51. Can continuous, feed-and-bleed ultrafiltration be staged? If so, how many retentates and how many permeates are obtained?

52. What is diafiltration? How does it differ from continuous, feed-and-bleed ultrafiltration? Under what conditions is diafiltration used in conjunction with continuous, feed-and-bleed ultrafiltration?

**Section 14.9:**

53. What are the two types of membrane structures used in microfiltration?

54. What is the difference between dead-end and tangential-flow microfiltration?

55. In microfiltration, why is operation that combines constant-flux and constant-pressure operation used?
Chapter 15

1. In adsorption operations, what is the adsorbate and the adsorbent?

2. How is a high surface achieved for adsorption?

3. What is meant by ion exchange? How does ion exchange differ from deionization?

4. What kinds of sorbents are used in chromatography?

5. In adsorption processes, what distinguishes a purification from a bulk separation?

6. What three inventions made possible the bulk separation of mixtures by adsorption?

7. What is meant by regeneration?

Section 15.1:

8. What are the 10 major requirements of an effective adsorbent?

9. Can the specific surface area of an adsorbent be estimated from its average pore diameter? If so, what equation is used and under what assumptions is it derived?

10. Why is it easy to measure the amount of adsorption of a pure gas, but difficult to measure the adsorption of a pure liquid?

11. Name five of the most important commercial adsorbents? What is the distinguishing feature of the molecular-sieve zeolites?

12. What is the BET equation used for? Does it assume physical or chemical adsorption? Does it assume monomolecular or multimolecular layers adsorption?

13. What experimental techniques can be used to measure pore-size distribution?
14. What kinds of materials are most commonly used as ion exchangers? How are they made?

15. What are the different types of chromatographic methods?

16. How is possible to use a liquid sorbent in chromatography?

Section 15.2:

17. What is meant by loading in adsorption?

18. What is an adsorption isotherm? How can the heat of adsorption be determined from a series of isotherms?

19. What is capillary condensation? What effect does it have on an adsorption isotherm?

20. In Figure 15.9, which isotherm(s) is (are) favorable and which unfavorable?

21. What is the equation for a linear adsorption (also called Henry's law)?

22. What is the major difference between the shapes of the isotherms predicted by the Freundlich and Langmuir isotherms? Which one is based on theory?

23. What is meant by an extended adsorption isotherm?

24. What makes the determination of an equation for an adsorption isotherm of a binary or multicomponent liquid mixture difficult, leading to weird-shaped curves as shown in Figure 15.13?

25. Why is the maximum loading of an ion exchanger fixed? What fixes it?

26. Does the valences of the ions being exchanged influence the equilibrium expression? How?
Section 15.3:

27. What are the four steps that occur during the adsorption of a solute from a gas or liquid mixture? Which step is almost instantaneous such that equilibrium can be assumed?

28. Within the particle, why are mass and heat transfer not analogous?

29. For mass transfer outside a spherical particle, what is the smallest value of the Sherwood number? What is the basis for this value?

30. What is the recommended equation for predicting the external mass-transfer coefficient for flow through a packed bed of particles?

31. What mechanisms of internal mass transfer must be considered for gas adsorption?

Section 15.4:

32. What is the difference between slurry adsorption (contact filtration) and fixed-bed adsorption (percolation)? When should each be considered and not considered?

33. How do pressure-swing and thermal-swing adsorption differ?

34. What are inert-purge swing and displacement purge?

35. What is meant by a simulated countercurrent adsorption system?

36. What is the advantage of the rotating, cross-current, annular chromatograph?

37. What are the three common modes for conducting slurry adsorption? Which mode requires the smallest residence time of the liquid mixture? What controls the rate of slurry adsorption, external or internal mass transfer?
38. What is ideal fixed-bed adsorption? What assumptions are necessary for it to apply? What is meant by the stoichiometric front? What is meant by breakthrough?

39. What is a mass-transfer zone (MTZ) and what causes it? Is it desirable? If not, why not?

40. For fixed-bed adsorption, what is the difference between the superficial velocity, interstitial velocity, and the concentration wave velocity? Which is the largest and which is the smallest?

41. Explain what each term means in Equation (15-102).

42. What is the linear driving-force (LDF) model of Glueckauf? Why is it so useful?

43. Why is Equation (15-106) useful? Does it account for both external and internal mass transfer?

44. What is the Klinkenberg approximation? Why is it useful in computing concentration and loading profiles, and breakthrough curves for fixed-bed adsorption?

45. What is the Collins technique for sizing a fixed-bed adsorption vessel?

46. Describe a typical thermal-swing adsorption cycle.

47. What is meant by the delta loading?

48. What is the basis for the method of lines for solving partial differential equations?

49. What is the difference between pressure-swing and vacuum-swing adsorption?

50. Describe the steps in the Skarstrom cycle.

51. How is the McCabe-Thiele diagram used for continuous, countercurrent adsorption-desorption?
52. What is the difference between a true-moving-bed (TMB) system and a simulated-moving-bed (SMB) system?

53. Why is it difficult to carry out a continuous, countercurrent adsorption process using a true-moving-bed (TMB) system?

54. Under what conditions is a circulating desorbent used to separate a binary mixture by a SMB system?

55. How is port switching used in an SMB system?

56. Why are sections used in an SMB system?

57. What is the difference between component composition profiles achieved for a four-section TMB system between a local adsorption equilibrium model and a rate-based adsorption model?

58. How is the triangle method used to determine approximate necessary values for flowrate ratios in a TMB unit?

59. What are the assumptions made in the steady-state TMB model?

60. How does the dynamic SMB model differ from the TMB model?

61. Can axial dispersion be significant in SMB systems?

62. Describe a typical ion exchange cycle.

63. In chromatography, what causes different solutes to pass through the chromatograph with different residence times?

64. In chromatography, what is the difference between the equilibrium wave pulse theory and the rate-based theory?
Chapter 16

1. Is leaching synonymous with solid-liquid and/or liquid-solid extraction?

2. In a leaching operation, what is the leachant, the overflow, and the underflow?

3. Why does the underflow consist of both leached solids and liquid containing leached material?

4. Name two important industrial applications of leaching.

Section 16.1:

5. Why is pretreatment of the solids to be leached often necessary?

6. Under what conditions would leaching be expected to be very slow?

7. What is dissolution?

8. What is the difference between suspension leaching and percolation leaching? For what conditions is each method used?

9. What are the advantages of the espresso machine over the drip method?

10. Can leaching be carried out on a continuous basis?

11. Why do many leaching processes include multistage, countercurrent washing after the leaching stage?

Section 16.2:

12. What are the assumptions for an ideal leaching or washing stage?

13. For leaching and washing calculations, when is the use of the McCabe-Smith algebraic method preferred over the McCabe-Thiele graphical method.
14. What is meant by variable underflow and what causes it?

Section 16.3:

15. How does the shrinking-core model used for mineral leaching differ from the simpler model used for leaching of food materials?

16. Why is an effective diffusivity that is obtained by experiment preferred for estimating the rate of leaching of food materials?

17. What is the pseudo-steady-state assumption used in the shrinking-core leaching model?
Chapter 17

1. How does solution crystallization differ from melt crystallization?

2. Under what conditions does precipitation occur?

3. What is meant by watering-out and salting-out?

4. What are the two main methods used to cause crystallization from an aqueous solution? Which is more common and why?

5. What is zone refining?

6. What is the difference between crystallization and desublimation?

7. What is the difference between mother liquor and magma?

8. Why is a crystallization operation often preceded by one or more stages of evaporation?

Section 17.1:

9. What is difference between an amorphous solid and a crystalline solid?

10. Why are crystals never spherical in shape?

11. What do two crystals of a given chemical have in common?

12. What is meant by crystal habit?

13. What is a crystal space lattice? How many different lattices are possible?

14. Why can crystals of a given chemical be plates, needles, or prisms?

15. Can a commercial crystallizer produce crystals all of the same size or is a distribution of sizes always obtained?
16. What are the methods for measuring particle size of crystals that can be seen by the human eye?

17. What is the range of aperture opening, in microns, for U.S. Standard Screens?

18. What constitutes a screen analysis?

19. What is the difference between a differential screen analysis and a cumulative screen analysis?

20. What is the difference between oversize and undersize cumulative screen analyses?

21. Four different mean particle diameters can be calculated from a screen analysis. What are they and how do they differ?

**Section 17.2:**

22. Does the solubility of most inorganic compounds in water increase or decrease with temperature?

23. What is the solubility product? Is it used with very soluble or sparingly soluble inorganic compounds?

24. What is a hydrate of an inorganic compound? Why does it form?

25. Can an inorganic compound have more than one form of hydrate?

26. Solution crystallization may be caused by cooling and/or evaporation. When is cooling not effective?

27. What is the difference between the integral heat of solution at saturation and the heat of crystallization? Which is exothermic?

28. What is the heat of dilution?
Section 17.3:

29. Is the commonly reported solubility of an inorganic compound in water for large crystals or small crystals?

30. What is supersaturation? Under what conditions is it possible to supersaturate a solution? What is the metastable region?

31. What is the difference between primary and secondary nucleation?

32. In physical adsorption, the resistance to the rate of adsorption at the solid-fluid interface is negligible. Is that true for solution crystallization? If so, why?

Section 17.4:

33. What is the difference between a continuous, cooling crystallizer and a continuous, vacuum, evaporating crystallizer?

34. Why is the draft-tube, baffled (DTB) crystallizer popular. What are its main features? What is a draft tube?

Section 17.5:

35. What are the assumptions of the MSMPR crystallization model?

36. What is a crystal-population balance?

37. How does the MSMPR model predict the predominant crystal size?

Section 17.6

38. Why are the crystals formed during precipitation so small?

39. During precipitation, is supersaturation large or small?
Section 17.7:

40. What is a eutectic? What is the difference between a eutectic-forming system and a solid-solution forming system?

41. What are two main types of equipment for carrying out melt crystallization?

42. What types of compounds are amenable to separation by melt crystallization?

43. What is zone melting? Why is it capable of producing pure components from solid-solution forming mixtures?

Section 17.9:

44. Under what conditions can a component of a gas mixture be directly crystallized (desublimated), bypassing the liquid phase?

45. What are the four techniques for causing desublimation?

Section 17.10:

46. Why are there several different types of evaporation equipment?

47. Why do some evaporators operate under vacuum? How is the vacuum produced?

48. Why do aqueous inorganic solutions exhibit a boiling-point rise over the boiling point of pure water? Is it possible to have a boiling-point decrease?

49. What are the key assumptions in the evaporator model?

50. Is the rate of evaporation from an aqueous inorganic solution computed from heat transfer or mass transfer?

51. What is a multiple-effect evaporator system? Why is it sometimes used?
52. What is the difference between forward feed and backward feed in a multiple-effect evaporator system? What favors a backward feed?
Chapter 18

1. What are some of the industrial applications of drying?

2. What are the most commonly employed modes of heat transfer for drying? Does the temperature of the solid during drying depend on the mode?

Section 18.1:

3. Why is there such a large variety of drying equipment?

4. When is a batch dryer usually preferred over a continuous dryer?

5. What is the difference between a direct-heat dryer and an indirect-heat dryer?

6. For a tray dryer, under what conditions can hot air be passed through the solids? When must the hot air be passed over the solids in the tray?

7. When are agitated batch dryers used?

8. What types of continuous dryers can be used with wet, solid particles?

9. What is the difference between a direct-heat and an indirect-heat rotary dryer?

10. For what types of wet solids can fluidized-bed, spouted-bed, and pneumatic-conveyor dryers be used?

11. What types of dryers can be used with slurries?

12. How does infrared, dielectric, and microwave drying differ from direct-heat drying?

13. What is freeze drying and when is it a good choice?
Section 18.2:

14. What is psychrometry?

15. What are the differences among absolute humidity, relative humidity, and percentage humidity?

16. What is the wet-bulb temperature? How is it measured? How does it differ from the dry-bulb temperature?

17. What is the adiabatic-saturation temperature? Why is it almost identical to the wet-bulb temperature for the air-water system?

18. For systems other than air-water, why is the wet-bulb temperature always higher than the adiabatic-saturation temperature?

19. What is the psychrometric ratio? How is it related to the Lewis number? What is the Lewis number?

20. Under what drying conditions is the moisture evaporation temperature equal to the wet-bulb temperature?

Section 18.3:

21. Distinguish between:
   - Total-moisture content
   - Free-moisture content
   - Equilibrium-moisture content
   - Unbound moisture
   - Bound moisture

22. How does the equilibrium-moisture content depend on temperature and relative humidity?

23. How does hysteresis affect equilibrium-moisture content?
Section 18.4:

24. What are the different periods that may occur during a drying operation?
25. Under what conditions is a constant-rate-drying period observed?
26. Under what conditions is a falling-rate-drying period observed?
27. What is the critical-moisture content?
28. What are the two most applied theories to the falling-rate-drying period?

Section 18.5:

29. In the dryer models for a belt dryer with through-circulation and a direct-heat rotary dryer, is the rate of drying based on heat transfer or mass transfer?
30. What is achieved by using a multiple-zone, through-circulation belt dryer with hot air flow reversal between zones?
31. What are the regimes of fluidization of a bed of particles by a gas? What regime of operation is preferred for drying?
2. Answers to Selected Odd-Numbered Exercises

Chapter 1

1.15  (a)  
Flow rate, kmol/h:

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed, C-1</th>
<th>Dist., C-1</th>
<th>Bot., C-1</th>
<th>Dist., C-2</th>
<th>Bot., C-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>200.00</td>
<td>192.00</td>
<td>8.00</td>
<td>8.00</td>
<td>0.00</td>
</tr>
<tr>
<td>E</td>
<td>175.00</td>
<td>3.92</td>
<td>171.08</td>
<td>166.25</td>
<td>4.83</td>
</tr>
<tr>
<td>IP</td>
<td>75.00</td>
<td>0.00</td>
<td>75.00</td>
<td>6.46</td>
<td>68.54</td>
</tr>
<tr>
<td>NP</td>
<td>50.00</td>
<td>0.00</td>
<td>50.00</td>
<td>0.00</td>
<td>50.00</td>
</tr>
<tr>
<td>Totals</td>
<td>500.00</td>
<td>195.92</td>
<td>304.08</td>
<td>180.71</td>
<td>123.37</td>
</tr>
</tbody>
</table>

(b) 96.08%
(c) 95.41%
(d) 97.76%

1.17  (a)  
Flow rate, kmol/h:

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Feed</th>
<th>Retentate</th>
<th>Permeate</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>42.4</td>
<td>16.8</td>
<td>25.6</td>
</tr>
<tr>
<td>CH₄</td>
<td>7.0</td>
<td>6.7</td>
<td>0.3</td>
</tr>
<tr>
<td>N₂</td>
<td>0.5</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Totals</td>
<td>49.9</td>
<td>24.0</td>
<td>25.9</td>
</tr>
</tbody>
</table>

(b) 98.8%
(c) 37°C for retentate
-57°C for permeate
Chapter 2

2.1  2,060 kJ/h

2.3  (a)  26,360,000 kJ/h
     (b)  16,520 kJ/h-K
     (c)  4,925,000 kJ/h
     (d)  373,000 kJ/h
     (e)  7.04 %

2.5  (a), (d), and (f) are rigorous.
     (b) assumes ideal solutions.
     (c) assumes ideal gas, ideal gas solution, and ideal liquid solution.
     (e) assumes ideal gas, ideal gas solution, ideal liquid solution, and low pressure.
     (g) assumes ideal gas, ideal gas solution, and low pressure.

2.7  (a) $K_D$ of isoctane in II relative to I = 0.456
     $K_D$ of furfural in II relative to I = 17.75
     (b) Relative selectivity = 0.00257
     (c) $\gamma$ of isoctane in I = 21.95
         $\gamma$ of furfural in II = 17.75

2.11 31,380,000 kJ/h

2.13 427 kg/m³

2.17 5,844 ft³/h feed
     5,876 ft³/h waste gas
     4,162 ft³/h natural gas

2.21 412 kJ/kmol of feed
Chapter 3

3.1 \( x \) of ethyl alcohol = 0.566  
\( x \) of ethyl acetate = 0.434

3.3 0.00464 lbmol/ h-ft\(^2\)

3.5 (a) 5\( \times 10^{-9} \) mol/s  
(c) 0

3.7 (a) Nitrogen diffusivity = 1.033 cm\(^2\)/s  
Nitrogen rate of diffusion = 1.86 \( \times 10^{-8} \) mol/s

3.9 0.028 cm\(^2\)/s

3.11 Wilke-Chang:
(a) 1.89 \( \times 10^{-5} \) cm\(^2\)/s  
(b) 0.98 \( \times 10^{-5} \) cm\(^2\)/s  
(c) 2.03 \( \times 10^{-5} \) cm\(^2\)/s  
(d) 4.00 \( \times 10^{-5} \) cm\(^2\)/s

3.15 (a) 1.43 \( \times 10^{-5} \) cm\(^2\)/s  
(b) 0.056 cm\(^2\)/s  
(c) 8.01 \( \times 10^{-7} \) mol/s-cm  
(d) 4.43 \( \times 10^{-6} \) mol/s-cm

3.17 2.1 \( \times 10^{-5} \) cm\(^2\)/s

3.19 0.022 cm\(^2\)/s

3.21 0.028 mol/m\(^2\)-s for methane  
0.042 mol/m\(^2\)-s for hydrogen

3.23 54 h

3.25 28.7 h

3.27 4.4 cm

3.29 (a) 2.54 \( \times 10^{-6} \) kmol/s-m\(^2\)  
(b) 1.79 \( \times 10^{-6} \) kmol/s-m\(^2\)

3.31 (b) 5.23 \( \times 10^{-4} \) g  
(c) 1.96 \( \times 10^{-6} \) g  
(d) 380 s  
(e) 0.00086 cal/s  
Not sufficient, droplet temperature will decrease.

3.33 3.44 \( \times 10^{-5} \) kmol/s-m\(^2\)

3.35 \( k_c = 0.315 \) cm/s  
Film thickness = 0.051 cm

3.37 1.35 \( \times 10^{-5} \) cm\(^2\)/s

3.39 \( k_p = 0.893 \) lbmol/h-ft\(^2\)-atm if given air rate includes ammonia
Chapter 4

4.1 (a) For each of 7 streams: total flow, $T$, $P$, and $C$ mole fractions. Also, the rate of heat transfer, $Q$. Total of $7C + 22$ variables. (b) $C$ component material balances
   1 energy balance
   2 pressure identities
   2 temperature identities
   7 mole fraction sums
   $2C$ K-value expressions

Total of $3C + 12$ independent equations. (c) $4C + 10$ degrees of freedom (d) For each of 4 entering streams, specify: total flow, $T$, $P$, and $C$ mole fractions. Specify also one exit pressure and $Q$. Specifications other than $Q$ are possible, e.g. one exit temperature.

4.3 (a) $3C + 9$  
(b) $2C + 6$  
(c) $C + 3$  
(d) All feed conditions plus exit pressure.

4.5 4  
Fix temperature, pressure, & mole fractions of oxygen and argon in the air.

4.7

<table>
<thead>
<tr>
<th>$P$, kPa</th>
<th>kg SA/kg W</th>
</tr>
</thead>
<tbody>
<tr>
<td>101.3</td>
<td>0.0438</td>
</tr>
<tr>
<td>75.0</td>
<td>0.0592</td>
</tr>
<tr>
<td>25.0</td>
<td>0.1790</td>
</tr>
<tr>
<td>10.0</td>
<td>0.4553</td>
</tr>
<tr>
<td>3.3</td>
<td>1.4650</td>
</tr>
</tbody>
</table>

4.11 Molar ratio of $L$ to $V$ in feed = 4

4.13 Temperature of azeotrope = 53.5°C Composition of azeotrope = 65 mol% chloroform minimum-boiling azeotrope

4.15 (b) 57 mol% isopropanol  
(c) 50 mol% isopropanol in vapor  
14 mol% isopropanol in liquid  
(d) At 80°C, no vapor  
At 89°C, $K$ of isopropanol = 10, $K$ of water = 0.67, $\alpha = 15$

4.19 20.6% of benzene is vaporized

4.27 126 psia

4.29 (a) 67.64 kmol vapor  
(b) 0 vapor  
(c) 100 kmol vapor  
(d) 100 kmol vapor

4.31 211°F

4.33 bubble point = 101.6°C
dew point = 105.8°C  
At 103.7°C, $V/F = 0.49$  
$x_w = 0.41$, $y_w = 0.594$
4.35  
(a) $73.5^\circ C$, $y_{acetate} = 0.730$
(b) $74.3^\circ C$, $x_{acetate} = 0.867$
(c) $72.46^\circ C$, $x_{acetate} = 0.544$

4.39  
(a) $-61^\circ F$
(b) $-43.6^\circ F$

4.41  
$V_F = 194$ kmol/h
$L_F = 262$ kmol/h

4.45  
<table>
<thead>
<tr>
<th>Solvent</th>
<th>kg/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>MeAc</td>
<td>74,000</td>
</tr>
<tr>
<td>IPE</td>
<td>221,500</td>
</tr>
<tr>
<td>Hd</td>
<td>305,000</td>
</tr>
<tr>
<td>CHCl$_3$</td>
<td>535,300</td>
</tr>
</tbody>
</table>

4.49  
(a) 133.4 kg of extract with 9.1 wt% A, 2.9 wt% W, and 88 wt% E
86.6 kg of raffinate with 20.6 wt% A, 76.3 wt% W, and 3.1 wt% E
Ether-free extract is 75.8 wt% A and 24.2 wt% W
(b) 85 kg of raffinate with 42.5 wt% A, 50.5 wt% W, 7 wt% E

4.51  
Extract = 120.9 lbmol/h
Raffinate = 89.1 lbmol/h

4.53  
Overflow is 3,210 kg/h of 25.2 wt% carbonate
Underflow is 2,400 kg/h of solid oxide, and 2,140 kg/h of liquid containing 25.2 wt% carbonate

4.55  
2,500 lb/h of naphthalene crystals
3,500 lb/h of mother liquor containing 31.5 wt% naphthalene

4.57  
3,333 kg/h of benzene crystals
6,667 kg/h of mother liquor containing 85 wt% benzene

4.59  
3,800 kg of added water

4.61  
(a) $q_B = 0.6733c_B^{0.509}$
(b) 29,100 kg adsorbent

4.65  
(a) 89.3%
(b) 93.9%
(c) 98.5%

4.67  
Vapor = 1.805 moles adsorbate = 0.195 moles
$y = 0.67$
$x = 0.41$

4.69  
(a) 3,600 lb
(b) 972.9 lb
(c) 4.38 psia

4.73  
$70.8^\circ C$
23 mol% toluene
13 mol% ethyl benzene
64 mol% water

4.75  
$V = 359.78$ kmol/h
org. $L= 613.36$ kmol/h
aq. $L = 572.86$ kmol/h
Chapter 5

5.5 \[1,600 \text{ kg/h} = S_{\text{min}}\]
\[S/S_{\text{min}}=2.5\]
% recovery from 86.83% to 99.996%

5.7 Two stages are much better.

5.9 (a) 130.8 g  
(b) 62.9 g  
(c) 36.9 g  
(d) 33.5 g  
(e) 13.1 g

5.11 (a) 11,090 kg  
(b) 4,050 kg  
(c) 2,270 kg  
(d) 1,748 kg  
(e) 554 kg

5.13 Crosscurrent extraction:
For 2-5 stages, % extraction varies from 52.4-56.3%.
Countercurrent extraction:
For 2-5 stages, % extraction varies from 63.1-78.7%.

5.15 Flow rate, lbmol/h:

<table>
<thead>
<tr>
<th>Component</th>
<th>Exit vapor</th>
<th>Exit liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>150.1</td>
<td>9.9</td>
</tr>
<tr>
<td>Ethane</td>
<td>278.1</td>
<td>91.9</td>
</tr>
<tr>
<td>Propane</td>
<td>93.8</td>
<td>146.2</td>
</tr>
<tr>
<td>n-Butane</td>
<td>1.5</td>
<td>23.6</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>0.3</td>
<td>6.3</td>
</tr>
<tr>
<td>Oil</td>
<td>0.1</td>
<td>328.3</td>
</tr>
</tbody>
</table>
Get more absorption with twice the absorbent rate and half of the trays.

5.17 % absorption:

<table>
<thead>
<tr>
<th>Component</th>
<th>(a) 125°F</th>
<th>(b) 150°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_1</td>
<td>2.58</td>
<td>2.34</td>
</tr>
<tr>
<td>C_2</td>
<td>10.31</td>
<td>8.59</td>
</tr>
<tr>
<td>C_3</td>
<td>28.24</td>
<td>22.91</td>
</tr>
<tr>
<td>nC_4</td>
<td>74.09</td>
<td>59.32</td>
</tr>
<tr>
<td>nC_5</td>
<td>93.08</td>
<td>88.93</td>
</tr>
</tbody>
</table>

% absorption decreases with increasing temperature

5.19 kmol/h:

<table>
<thead>
<tr>
<th>Component</th>
<th>l_{out}</th>
<th>v_{out}</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_1</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>C_2</td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>C_3</td>
<td>0</td>
<td>18.2</td>
</tr>
<tr>
<td>nC_4</td>
<td>0.1</td>
<td>44.6</td>
</tr>
<tr>
<td>nC_5</td>
<td>1.4</td>
<td>84.5</td>
</tr>
<tr>
<td>nC_{10}</td>
<td>680.0</td>
<td>168.7</td>
</tr>
<tr>
<td></td>
<td>681.5</td>
<td>318.5</td>
</tr>
<tr>
<td>Steam</td>
<td>1,000.0</td>
<td>1,318.5</td>
</tr>
</tbody>
</table>

Dew point of vapor out = 287°F

5.21 Reflux rate, lbmol/h \[d/b\text{ for } C_3\]

<table>
<thead>
<tr>
<th>Reflux rate lbmol/h</th>
<th>d/b for C_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>0.0114</td>
</tr>
<tr>
<td>1,500</td>
<td>0.00522</td>
</tr>
<tr>
<td>2,000</td>
<td>0.00322</td>
</tr>
<tr>
<td>2,500</td>
<td>0.00237</td>
</tr>
</tbody>
</table>

Increasing the reflux rate enhances the separation
### 5.23

<table>
<thead>
<tr>
<th>Component</th>
<th>$d$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_2$</td>
<td>29.999</td>
<td>0.001</td>
</tr>
<tr>
<td>C$_3$</td>
<td>192.663</td>
<td>7.337</td>
</tr>
<tr>
<td>nC$_4$</td>
<td>7.325</td>
<td>362.674</td>
</tr>
<tr>
<td>nC$_5$</td>
<td>0.012</td>
<td>349.988</td>
</tr>
<tr>
<td>nC$_6$</td>
<td>0</td>
<td>50.00</td>
</tr>
</tbody>
</table>

### 5.25

Partial reboiler:
- $N_V = 3C + 10$
- $N_E = 2C + 6$
- $N_D = C + 4$

Total Condenser:
- $N_V = 2C + 7$
- $N_E = C + 3$
- $N_D = C + 4$

### 5.27

Need 5 more specifications

### 5.29

Add 2 degrees of freedom when adding a vapor sidestream

### 5.33
(a) $2N + 2C + 11$
(b) Need 5 additional specifications

### 5.35
19 degrees of freedom
Need 15 more specifications

### 5.37
For $C = 3$,
(a) $13(N + M) + 50$
(b) $11(N + M) + 31$
(c) $2(N + M) + 19$

### 5.39
(a) $7(N + M) + 2C(N + M) + 7C + 28$
(b) $5(N + M) + 2C(N + M) + 6C + 13$
(c) $2(N + M) + C + 15$

### 5.41
One more specification is needed, e.g. saturated liquid leaving condenser
Chapter 6

6.1 Stripping of water is 22 kmol/h
Absorption of acetone is 10.3 kmol/h
More stripping than absorption
However, operation is absorption because a high percentage of acetone is absorbed.

6.5 Advantages of air are ready availability and low cost.
Disadvantage of air is the possibility of forming a flammable mixture.

6.7 (a) 1.74 mol amine solution/mol feed gas
(b) 2.34 mol% CO₂

6.9 (a) 0.30
(b) 9 to 10
(c) 0.33

6.11 4,377 scfm of air
13 equilibrium stages
ppm in drinking water: DCA 0.005, TCE 0.000, and TCA 0.000.

6.13 Exit Liquid, lbmol/h:

<table>
<thead>
<tr>
<th>Comp</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>14.0</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>C₂</td>
<td>6.5</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>C₃</td>
<td>12.3</td>
<td>22.6</td>
<td>22.9</td>
</tr>
<tr>
<td>nC₄</td>
<td>21.2</td>
<td>33.2</td>
<td>37.3</td>
</tr>
<tr>
<td>nC₅</td>
<td>22.7</td>
<td>22.9</td>
<td>23.9</td>
</tr>
</tbody>
</table>

6.15 Drickamer-Bradford: 10.8%
O’Connell: 18.9%

6.17 (a) \( E_o = 0.50 \)
(b) \( E_o = 0.63 \)
\( E_{MV} = 0.67 \)
(c) \( E_o = 0.62 \)
\( E_{MV} = 0.66 \)

6.19 Flooding Velocity = 0.272 ft/s
Diameter = 3.53 ft

6.21 (a) Diameter = 1.15 m
(b) Pressure Drop = 0.076 psi/tray
(c) \( E_{OV} = 0.76 = 76\% \)

6.23 (a) 3
(b) 6.0 ft
(c) 0.13 psi/tray
(d) 0.064 = 6.4%
(e) 47 trays if well mixed,
(f) 15 trays if plug flow of liquid

6.25 (a) 57.5% absorbed
(b) 0.0055 lbmol/ft³

6.27 (a) 0.071 kg/s
(b) GeCl₄ controls
\( 8.3 \) ft
(c) For 10 ft,
\% absorption of GeCl₄ = 99.6%
\% absorption of GeCl₂ = 99.99%

6.29 \( k_{GA} = 0.0234 \text{ s}^{-1} \)
\( k_{Gα} = 1.73 \text{ s}^{-1} \)
6.31  (a) $\frac{1,304}{768} = 1.70$
(b) $0.0179$ mol CO$_2$/mol caustic solution
(c) 7.3 theoretical stages
(d) 1.826 lbmol/h
(e) column floods, must increase diameter
(f) 8.5 overall gas transfer units
(g) 177 ft packing height for 4.4 ft diameter (50% flooding)

6.33  1.61 ft$^3$

6.35  (a) 594,000 kg/h
(b) $N_{OG} = 3.573$

6.37  (a) 1.70
(b) 0.01736 mole fraction
(c) 7.5 stages
(d) $N_{OG} = 8.7$
(e) Packed height varies from 7.38 to 23.6 ft for $L'/V' = 10$ to 2

6.39  (a) $X = 0.01896 \left[ \frac{y}{1-y} \right] - 0.000095$
(b) $N_{OG} = 5.16$
Chapter 7

7.3 Condenser temperature must be below critical temperature of -115°F for methane. Might operate column at a top pressure of 415 psia and a corresponding temperature of -143°F, using R-14 (carbon tetrafluoride) refrigerant at -150°F and 70 psia.

7.9 (a) 90.4 mol%
(b) 87.435 mols/100 mols of feed
(c) 7 to 8 stages

7.11

<table>
<thead>
<tr>
<th>Procedure</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62.9</td>
<td>1.5</td>
<td>53.0</td>
</tr>
<tr>
<td>2</td>
<td>67.2</td>
<td>1.5</td>
<td>49.5</td>
</tr>
<tr>
<td>3</td>
<td>68.8</td>
<td>1.5</td>
<td>48.0</td>
</tr>
<tr>
<td>4</td>
<td>67.2</td>
<td>1.5</td>
<td>49.5</td>
</tr>
<tr>
<td>5</td>
<td>78.3</td>
<td>1.5</td>
<td>34.2</td>
</tr>
</tbody>
</table>

Procedure 5 is best.

7.13 (a) 12.1 kg/h distillate and 17.9 kg/h bottoms.
(b) 10 to 11 stages + partial reboiler

7.15 (a) Yes

7.17 (a) (1) 1.092
(2) 18 mol% benzene
(3) 41.0 moles distillate
(b) (1) 2.23
(2) 8 mol% benzene
(3) 47.7 moles distillate
(c) (2) 7 mol% benzene
(3) 48.3 moles distillate

7.19 Assuming a saturated liquid feed, condenser cooling water leaks in.
No, 90% product can not be obtained.

7.21 8 stages and a partial reboiler

7.23 20 stages and partial reboiler
Feed at stage 17 from top

7.25 63.49 kmol

7.27 (a) 1.79 minimum reflux ratio
  0.959 minimum boilup ratio
  6 minimum stages (5 + reboiler)
(b) 10 actual trays + reboiler
7.29  (a) 0.777 mol% ethanol in bottoms  
(b) (1) Min $L/V = 0.65$  
(2) Min $R = 1.86$  
(3) Min boilup ratio = 0.846  
(c) 9 + reboiler theoretical stages  
18.2 minimum plates  
(d) 26 plates + reboiler  

7.31  (a) Above intercoolers:  
\[ y = 0.333x + 0.633 \]  
Between intercooler and feed:  
\[ y = 0.667x + 0.317 \]  
Below feed:  
\[ y = 1.542x - 0.026 \]  
(b) 4 stages and reboiler  

7.33  (a) approx. 15 theoretical stages  
(b) approx. 15 theoretical stages  
(c) approx. 8 stages  

7.35  32 stages and reboiler  
Feed stages at stages 17 and 27 from the top  

7.37  Without interreboiler, 8 minus stages  
With interreboiler, 8 plus stages  
Interreboiler at stage 3 from bottom at 162°C  

7.39  99 stages and reboiler  

7.41  (a) 73%  
(b) 44.6%  
(b) 55.9%  
(c) 77.4%  

7.43  2.9 ft  

7.45  16.2 ft high  
4.05 ft diameter  

7.47  (a) 21.2 ft above feed  
14.7 ft below feed  
Swage column  
(b) 10.1 ft diameter  
40.4 ft long  

7.49  (a) 95% above feed  
(unacceptable)  
51% below feed  
(b) 0.175 psi/tray above feed  
0.125 psi/tray below feed  
(c) 50% above feed  
1.7% below feed or 58 lbmol/h  
(d) 14.4 in. at top  
10.0 in. at bottom  

7.51  (a) 2 stages and a partial reboiler below the feed  
13.8 stages in rectifying the section  
(b) 2.4 stages below feed  
12.4 stages in rectifying section  
(c) 42.5 ft  
(d) 32 ft  

7.53  (a) 0.0294 m$^3$/m$^3$ at top  
0.0412 m$^3$/m$^3$ at bottom  
(b) 3.8 ft at top  
3.6 ft at bottom  
(d) 13.1 ft of packing  
(e) 0.11 psi
(a) 204°F
   0.75 mole fraction H in vapor
   and 0.35 mole fraction H in liquid

(b) 10,000 Btu/lbmol
   0.77 mole fraction H in vapor
   and 0.38 mole fraction H in liquid

(c) 60 mol% is vapor
   0.92 mole fraction H in vapor
   0.60 mole fraction H in liquid
Chapter 8

8.11 (a) 233 kg/h
       (b) 5 plus
       (c) Acetone mass fraction

<table>
<thead>
<tr>
<th>Stg</th>
<th>Raffinate</th>
<th>Extract</th>
<th>Raffinate flow rate, kg/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.390</td>
<td>0.509</td>
<td>935</td>
</tr>
<tr>
<td>2</td>
<td>0.325</td>
<td>0.440</td>
<td>822</td>
</tr>
<tr>
<td>3</td>
<td>0.260</td>
<td>0.360</td>
<td>738</td>
</tr>
<tr>
<td>4</td>
<td>0.190</td>
<td>0.270</td>
<td>650</td>
</tr>
<tr>
<td>5</td>
<td>0.100</td>
<td>0.165</td>
<td>580</td>
</tr>
</tbody>
</table>

8.13 2.5 equilibrium stages. Impossible.

8.15 Approximately 5 theoretical stages and 194.5 kg/h of DPH in extract at 45°C

8.17 5 minus stages
      Feed to stages 1 and 2

8.25 10 stages
      2.5
      16 stages with feed at stage 11 from the raffinate end

8.27 (a) 1.66
       (b) 11,790 kg/h
       (c) 11,830 kg/h

8.29 139,000 lb/h

8.31 (a) 0.32 mm
       (b) 0.96 mm
       (c) 1,234 ft²/ft³

8.33 (a) 81 rpm
       (b) 10 hp
       (c) 0.53 mm
       (d) 2,080 ft²/ft³
       (e) 0.202 ft/h
       (f) 26.3
       (g) 96.3%
       (h) 96.8% extracted

8.35 11 units in parallel of 1.5 m diameter each

8.37 19.4 inches
Chapter 9

9.1 Total condenser
30 psia or less

9.3 Column D-1: partial condenser,
31.4 psia
Column D-2: total condenser,
15 to 30 psia

9.5 (a) 7.1
(b) 5.3
(c) 2.3

9.7 8.4
Distribution:

<table>
<thead>
<tr>
<th>kmol/h: Component</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>2499.996</td>
<td>0.0042</td>
</tr>
<tr>
<td>iC4</td>
<td>399.63</td>
<td>0.37</td>
</tr>
<tr>
<td>nC4</td>
<td>594</td>
<td>6</td>
</tr>
<tr>
<td>iC5</td>
<td>15</td>
<td>85</td>
</tr>
<tr>
<td>nC5</td>
<td>6.12</td>
<td>193.88</td>
</tr>
<tr>
<td>nC6</td>
<td>0.001</td>
<td>39.999</td>
</tr>
<tr>
<td>nC7</td>
<td>8.2 x10^-7</td>
<td>50</td>
</tr>
<tr>
<td>nC8</td>
<td>1.92 x10^-10</td>
<td>40</td>
</tr>
</tbody>
</table>

9.9

<table>
<thead>
<tr>
<th>% rec. of C3</th>
<th>Distillate, lbmol/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>228.1</td>
</tr>
<tr>
<td>95</td>
<td>220.0</td>
</tr>
<tr>
<td>90</td>
<td>210.0</td>
</tr>
<tr>
<td>75</td>
<td>180.0</td>
</tr>
<tr>
<td>50</td>
<td>130.0</td>
</tr>
</tbody>
</table>

9.11 272.8 kmol/h
Distribution:

<table>
<thead>
<tr>
<th>Component</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>2500.0</td>
<td>0.0</td>
</tr>
<tr>
<td>iC4</td>
<td>400.0</td>
<td>0.0</td>
</tr>
<tr>
<td>nC4</td>
<td>594.0</td>
<td>6.0</td>
</tr>
<tr>
<td>iC5</td>
<td>15.0</td>
<td>85.0</td>
</tr>
<tr>
<td>nC5</td>
<td>17.9</td>
<td>182.1</td>
</tr>
<tr>
<td>nC6</td>
<td>0.0</td>
<td>40.0</td>
</tr>
<tr>
<td>nC7</td>
<td>0.0</td>
<td>50.0</td>
</tr>
<tr>
<td>nC8</td>
<td>0.0</td>
<td>40.0</td>
</tr>
</tbody>
</table>

9.13 17.73

9.15 Action is more important in the stripping section.
Gilliland correlation is empirical, based on the rectification section.
A correlation based on the stripping section would be more accurate.

9.17 (a) 6.38
(b) Distribution

<table>
<thead>
<tr>
<th>lbmol/h: Component</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>4.998</td>
<td>0.000</td>
</tr>
<tr>
<td>iC4</td>
<td>14.720</td>
<td>0.280</td>
</tr>
<tr>
<td>nC4</td>
<td>23.150</td>
<td>1.875</td>
</tr>
<tr>
<td>iC5</td>
<td>3.600</td>
<td>16.400</td>
</tr>
<tr>
<td>nC5</td>
<td>2.356</td>
<td>32.664</td>
</tr>
</tbody>
</table>

(c) Only distributing non-key is nC5,
with 1.36 lbmol/h to D
56.49 lbmol/h min. reflux
(d) 15.6 stages
(e) Stage 6 or 7 from the top
9.19  (a)  

<table>
<thead>
<tr>
<th>Component</th>
<th>$x_D$</th>
<th>$x_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.662</td>
<td>0.007</td>
</tr>
<tr>
<td>B</td>
<td>0.307</td>
<td>0.039</td>
</tr>
<tr>
<td>C</td>
<td>0.031</td>
<td>0.954</td>
</tr>
</tbody>
</table>

(b) $R_{\text{min}} = 0.447$
Minimum boilup ratio = 2.17
(c) 14 stages
Feed stage is 7 or 8 from the top

9.21  Apply the stripping factor version of Eqs (5-46) and (5-47) to $N = 2$ stages

9.23  % absorption:

<table>
<thead>
<tr>
<th>Comp.</th>
<th>$N = 4$</th>
<th>$N = 10$</th>
<th>$N = 30$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_1$</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>C$_2$</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>C$_3$</td>
<td>22.7</td>
<td>22.7</td>
<td>22.7</td>
</tr>
<tr>
<td>nC$_4$</td>
<td>68.4</td>
<td>75.5</td>
<td>76.9</td>
</tr>
<tr>
<td>nC$_5$</td>
<td>98.4</td>
<td>99.99</td>
<td>100.0</td>
</tr>
</tbody>
</table>

9.25  Products:  

<table>
<thead>
<tr>
<th>Component</th>
<th>$l$</th>
<th>$v_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_1$</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>C$_2$</td>
<td>0.1</td>
<td>2.1</td>
</tr>
<tr>
<td>C$_3$</td>
<td>3.3</td>
<td>14.9</td>
</tr>
<tr>
<td>nC$_4$</td>
<td>20.6</td>
<td>24.1</td>
</tr>
<tr>
<td>nC$_5$</td>
<td>61.8</td>
<td>24.1</td>
</tr>
</tbody>
</table>

9.27  Distribution:  

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Bottoms</th>
<th>Vapor out</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_1$</td>
<td>0.0</td>
<td>59.5</td>
</tr>
<tr>
<td>C$_2$</td>
<td>0.0</td>
<td>73.6</td>
</tr>
<tr>
<td>C$_3$</td>
<td>0.1</td>
<td>153.1</td>
</tr>
<tr>
<td>nC$_4$</td>
<td>25.9</td>
<td>147.6</td>
</tr>
<tr>
<td>nC$_5$</td>
<td>45.9</td>
<td>12.3</td>
</tr>
<tr>
<td>nC$_6$</td>
<td>27.4</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Chapter 10

10.5 \( x_1 = -100/6, \ x_2 = -100/3, \ x_3 = -100/3, \ x_4 = -100/3, \ x_5 = -100/3 \)

10.7 Yes

10.9 (a) \( x_1 = 1.0, \ x_2 = 4.0 \)
(b), (c), (d) method fails

10.11

\[
\begin{array}{cccc}
\text{Stg} & \text{Comp 1} & \text{Comp 2} & \text{Comp 3} & \text{Temp, } ^{\circ}\text{C} \\
1 & 0.7889 & 0.1798 & 0.0312 & 67.2 \\
2 & 0.6468 & 0.2550 & 0.0982 & 69.6 \\
3 & 0.4917 & 0.2902 & 0.2181 & 73.1 \\
4 & 0.3225 & 0.2991 & 0.3784 & 77.8 \\
5 & 0.1691 & 0.2460 & 0.5850 & 84.1
\end{array}
\]

10.13 Matrix structure is not block tridiagonal.

10.17 Change in ordering may be as or more efficient

10.21 Stage 8 or 9

10.23 Product Compositions, lbmol/h, using SRK:

\[
\begin{array}{ccc}
\text{Component} & \text{Distillate} & \text{Bottoms} \\
\text{C}_2 & 2.9998 & 0.0002 \\
\text{C}_3 & 19.5891 & 0.4110 \\
\text{nC}_4 & 0.4086 & 36.5914 \\
\text{nC}_5 & 0.0002 & 34.9998 \\
\text{nC}_6 & 0.0000 & 5.0000
\end{array}
\]

Stage temperatures from 115-264°F
Condenser duty = -0.8562 MMBtu/h
Reboiler duty = 1,014 MMBtu/h

10.25

Product Compositions, lbmol/h, with Grayson-Streed:

\[
\begin{array}{ccc}
\text{Component} & \text{Distillate} & \text{Bottoms} \\
\text{C}_3 & 4.9976 & 0.0024 \\
\text{iC}_4 & 14.7104 & 0.2896 \\
\text{nC}_4 & 23.4160 & 1.5840 \\
\text{iC}_5 & 3.7100 & 16.2900 \\
\text{nC}_5 & 2.0630 & 32.9371
\end{array}
\]

Temperatures from 161-230°F
Condenser duty = 1,002,600 Btu/h
Reboiler duty = 1,427,000 Btu/h

10.27

Product Composition , lbmol/h, with PR:

\[
\begin{array}{cccc}
\text{Dist} & \text{Bot} & \text{Liq} & \text{Vap} \\
\text{SS} & \text{SS} & \\
\text{nC}_4 & 13.630 & 0.000 & 0.450 & 0.000 \\
\text{nC}_5 & 0.45 & 0.000 & 18.944 & 0.136 \\
\text{nC}_6 & 0.000 & 1.217 & 0.136 & 23.427 \\
\text{nC}_7 & 0.000 & 38.723 & 0.000 & 1.217
\end{array}
\]

Temperatures from 48-289°F
Condenser duty = 2,834,600 Btu/h
Reboiler duty = 3,493,700 Btu/h

10.29 Suitable design with SRK:
23 stages (includes total condenser and partial reboiler)
Feed stage = 12 from the top
Reflux rate = 267.9 lbmol/h
Distillate rate = 52.11 lbmol/h
### 10.31 Using SRK:

(a) Reboiled Stripper with 4 stages

(b) lbmol/h:

<table>
<thead>
<tr>
<th>Component</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>3.3979</td>
<td>0.0021</td>
</tr>
<tr>
<td>Toluene</td>
<td>83.3960</td>
<td>1.2041</td>
</tr>
<tr>
<td>Diphenyl</td>
<td>0.1060</td>
<td>4.9940</td>
</tr>
</tbody>
</table>

(c) Adjust reboiler duty to 1,354,500 Btu/h

### 10.33 Using SRK:

Reflux ratio = 14

### 10.37 Product compositions, lbmol/h, with SRK

<table>
<thead>
<tr>
<th>Component</th>
<th>Gas Out</th>
<th>Oil Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
<td>272.216</td>
<td>13.784</td>
</tr>
<tr>
<td>C&lt;sub&gt;2&lt;/sub&gt;</td>
<td>124.058</td>
<td>32.942</td>
</tr>
<tr>
<td>C&lt;sub&gt;3&lt;/sub&gt;</td>
<td>94.475</td>
<td>145.525</td>
</tr>
<tr>
<td>nC&lt;sub&gt;4&lt;/sub&gt;</td>
<td>4.550</td>
<td>164.450</td>
</tr>
<tr>
<td>nC&lt;sub&gt;5&lt;/sub&gt;</td>
<td>0.078</td>
<td>147.922</td>
</tr>
<tr>
<td>nC&lt;sub&gt;10&lt;/sub&gt;</td>
<td>0.524</td>
<td>999.476</td>
</tr>
</tbody>
</table>

### 10.39 Using SRK for properties and assuming lean oil is nC<sub>12</sub>.

Flow rate, lbmol/h:

<table>
<thead>
<tr>
<th>Comp</th>
<th>Lean gas</th>
<th>Rich oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
<td>305.320</td>
<td>67.680</td>
</tr>
<tr>
<td>C&lt;sub&gt;2&lt;/sub&gt;</td>
<td>10.640</td>
<td>32.360</td>
</tr>
<tr>
<td>C&lt;sub&gt;3&lt;/sub&gt;</td>
<td>0.190</td>
<td>28.810</td>
</tr>
<tr>
<td>nC&lt;sub&gt;4&lt;/sub&gt;</td>
<td>0.002</td>
<td>18.998</td>
</tr>
<tr>
<td>nC&lt;sub&gt;5&lt;/sub&gt;</td>
<td>0.000</td>
<td>15.00</td>
</tr>
<tr>
<td>nC&lt;sub&gt;12&lt;/sub&gt;</td>
<td>0.010</td>
<td>384.990</td>
</tr>
</tbody>
</table>

### 10.41 Product Compositions with SRK

<table>
<thead>
<tr>
<th>Component</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.22</td>
<td>0.00</td>
</tr>
<tr>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
<td>59.51</td>
<td>0.00</td>
</tr>
<tr>
<td>C&lt;sub&gt;2&lt;/sub&gt;</td>
<td>73.57</td>
<td>0.00</td>
</tr>
<tr>
<td>C&lt;sub&gt;3&lt;/sub&gt;</td>
<td>153.09</td>
<td>0.13</td>
</tr>
<tr>
<td>nC&lt;sub&gt;4&lt;/sub&gt;</td>
<td>149.42</td>
<td>23.80</td>
</tr>
<tr>
<td>nC&lt;sub&gt;5&lt;/sub&gt;</td>
<td>13.75</td>
<td>44.47</td>
</tr>
<tr>
<td>nC&lt;sub&gt;6&lt;/sub&gt;</td>
<td>2.70</td>
<td>30.93</td>
</tr>
</tbody>
</table>

### 10.43 5 stages
Chapter 11

11.1

Binary azeotropes (all minimum boiling):

<table>
<thead>
<tr>
<th>Mixture, A/B</th>
<th>Boiling pt., °C</th>
<th>Wt% A/B</th>
<th>Mol% A/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Hexane/Methanol</td>
<td>50.6</td>
<td>49.0/51.0</td>
<td>49.0/51.0</td>
</tr>
<tr>
<td>n-Hexane/Methyl acetate</td>
<td>51.8</td>
<td>39.3/60.7</td>
<td>35.8/64.2</td>
</tr>
<tr>
<td>Methanol/Methyl acetate</td>
<td>53.5</td>
<td>19.0/81.0</td>
<td>35.2/64.8</td>
</tr>
</tbody>
</table>

Ternary azeotrope (minimum boiling):

<table>
<thead>
<tr>
<th>Mixture, A/B/C</th>
<th>Boiling pt., °C</th>
<th>Wt% A/B/C</th>
<th>Mol% A/B/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Hexane/Methanol/Methyl acetate</td>
<td>47.4</td>
<td>48.6/14.6/36.8</td>
<td>37.2/30.1/32.7</td>
</tr>
</tbody>
</table>

From an approximate residue curve map, the following types of nodes are determined using Fig. 11.6:

<table>
<thead>
<tr>
<th>Component or Azeotrope</th>
<th>Normal boiling pt., °C</th>
<th>Type node</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Hexane</td>
<td>69.0</td>
<td>stable</td>
</tr>
<tr>
<td>Methanol</td>
<td>64.7</td>
<td>stable</td>
</tr>
<tr>
<td>Methyl acetate</td>
<td>57.0</td>
<td>stable</td>
</tr>
<tr>
<td>n-Hexane/Methanol</td>
<td>50.6</td>
<td>saddle</td>
</tr>
<tr>
<td>n-Hexane/Methyl acetate</td>
<td>51.8</td>
<td>saddle</td>
</tr>
<tr>
<td>Methanol/Methyl acetate</td>
<td>53.5</td>
<td>saddle</td>
</tr>
<tr>
<td>n-Hexane/Methanol/Methyl acetate</td>
<td>47.4</td>
<td>unstable</td>
</tr>
</tbody>
</table>

11.3

<table>
<thead>
<tr>
<th>x (1)</th>
<th>x (2)</th>
<th>x (3)</th>
<th>y (1)</th>
<th>y (2)</th>
<th>y (3)</th>
<th>T, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3753</td>
<td>0.3594</td>
<td>0.2653</td>
<td>0.3731</td>
<td>0.3562</td>
<td>0.2707</td>
<td>47.84</td>
</tr>
<tr>
<td>0.3783</td>
<td>0.3635</td>
<td>0.2582</td>
<td>0.3753</td>
<td>0.3594</td>
<td>0.2653</td>
<td>47.84</td>
</tr>
<tr>
<td>0.3822</td>
<td>0.3689</td>
<td>0.2489</td>
<td>0.3783</td>
<td>0.3635</td>
<td>0.2582</td>
<td>47.85</td>
</tr>
<tr>
<td>0.3873</td>
<td>0.3757</td>
<td>0.2370</td>
<td>0.3822</td>
<td>0.3689</td>
<td>0.2489</td>
<td>47.86</td>
</tr>
<tr>
<td>0.3939</td>
<td>0.3840</td>
<td>0.2221</td>
<td>0.3873</td>
<td>0.3757</td>
<td>0.2370</td>
<td>47.89</td>
</tr>
<tr>
<td>0.2000</td>
<td>0.6000</td>
<td>0.2000</td>
<td>0.3939</td>
<td>0.3840</td>
<td>0.2221</td>
<td>47.99</td>
</tr>
<tr>
<td>0.0272</td>
<td>0.8662</td>
<td>0.1066</td>
<td>0.2000</td>
<td>0.6000</td>
<td>0.2000</td>
<td>55.01</td>
</tr>
<tr>
<td>0.0022</td>
<td>0.9586</td>
<td>0.0392</td>
<td>0.0272</td>
<td>0.8662</td>
<td>0.1066</td>
<td>61.89</td>
</tr>
<tr>
<td>0.0002</td>
<td>0.9869</td>
<td>0.0129</td>
<td>0.0022</td>
<td>0.9586</td>
<td>0.0392</td>
<td>63.74</td>
</tr>
<tr>
<td>0.0000</td>
<td>0.9958</td>
<td>0.0042</td>
<td>0.0002</td>
<td>0.9869</td>
<td>0.0129</td>
<td>64.25</td>
</tr>
<tr>
<td>0.0000</td>
<td>0.9987</td>
<td>0.0013</td>
<td>0.0000</td>
<td>0.9958</td>
<td>0.0042</td>
<td>64.41</td>
</tr>
<tr>
<td>0.0000</td>
<td>0.9996</td>
<td>0.0004</td>
<td>0.0000</td>
<td>0.9987</td>
<td>0.0013</td>
<td>64.46</td>
</tr>
</tbody>
</table>
11.5  

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>$x (1)$</th>
<th>$x (2)$</th>
<th>$x (3)$</th>
<th>$y (1)$</th>
<th>$y (2)$</th>
<th>$y (3)$</th>
<th>$T, ^\circ\text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.0</td>
<td>0.4458</td>
<td>0.4248</td>
<td>0.1294</td>
<td>0.6723</td>
<td>0.2519</td>
<td>0.0758</td>
<td>63.02</td>
</tr>
<tr>
<td>-0.9</td>
<td>0.4224</td>
<td>0.4425</td>
<td>0.1351</td>
<td>0.6558</td>
<td>0.2658</td>
<td>0.0784</td>
<td>63.53</td>
</tr>
<tr>
<td>-0.8</td>
<td>0.3985</td>
<td>0.4604</td>
<td>0.1411</td>
<td>0.6381</td>
<td>0.2807</td>
<td>0.0812</td>
<td>64.07</td>
</tr>
<tr>
<td>-0.7</td>
<td>0.3740</td>
<td>0.4786</td>
<td>0.1474</td>
<td>0.6189</td>
<td>0.2968</td>
<td>0.0843</td>
<td>64.67</td>
</tr>
<tr>
<td>-0.6</td>
<td>0.3491</td>
<td>0.4969</td>
<td>0.1540</td>
<td>0.5981</td>
<td>0.3141</td>
<td>0.0878</td>
<td>65.30</td>
</tr>
<tr>
<td>-0.5</td>
<td>0.3239</td>
<td>0.5151</td>
<td>0.1610</td>
<td>0.5758</td>
<td>0.3326</td>
<td>0.0916</td>
<td>65.99</td>
</tr>
<tr>
<td>-0.4</td>
<td>0.2986</td>
<td>0.5332</td>
<td>0.1682</td>
<td>0.5518</td>
<td>0.3525</td>
<td>0.0957</td>
<td>66.73</td>
</tr>
<tr>
<td>-0.3</td>
<td>0.2733</td>
<td>0.5509</td>
<td>0.1758</td>
<td>0.5259</td>
<td>0.3738</td>
<td>0.1003</td>
<td>67.52</td>
</tr>
<tr>
<td>-0.2</td>
<td>0.2483</td>
<td>0.5681</td>
<td>0.1836</td>
<td>0.4983</td>
<td>0.3964</td>
<td>0.1053</td>
<td>68.35</td>
</tr>
<tr>
<td>-0.1</td>
<td>0.2238</td>
<td>0.5845</td>
<td>0.1917</td>
<td>0.4690</td>
<td>0.4202</td>
<td>0.1108</td>
<td>69.23</td>
</tr>
<tr>
<td>0.0</td>
<td>0.2000</td>
<td>0.6000</td>
<td>0.2000</td>
<td>0.4381</td>
<td>0.4452</td>
<td>0.1167</td>
<td>70.14</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1762</td>
<td>0.6155</td>
<td>0.2083</td>
<td>0.4043</td>
<td>0.4726</td>
<td>0.1231</td>
<td>71.13</td>
</tr>
<tr>
<td>0.2</td>
<td>0.1534</td>
<td>0.6298</td>
<td>0.2169</td>
<td>0.3689</td>
<td>0.5010</td>
<td>0.1301</td>
<td>72.14</td>
</tr>
<tr>
<td>0.3</td>
<td>0.1318</td>
<td>0.6426</td>
<td>0.2255</td>
<td>0.3322</td>
<td>0.5303</td>
<td>0.1375</td>
<td>73.18</td>
</tr>
<tr>
<td>0.4</td>
<td>0.1118</td>
<td>0.6539</td>
<td>0.2343</td>
<td>0.2951</td>
<td>0.5596</td>
<td>0.1453</td>
<td>74.21</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0935</td>
<td>0.6633</td>
<td>0.2432</td>
<td>0.2581</td>
<td>0.5884</td>
<td>0.1535</td>
<td>75.23</td>
</tr>
<tr>
<td>0.6</td>
<td>0.0770</td>
<td>0.6708</td>
<td>0.2522</td>
<td>0.2218</td>
<td>0.6162</td>
<td>0.1620</td>
<td>76.21</td>
</tr>
<tr>
<td>0.7</td>
<td>0.0625</td>
<td>0.6763</td>
<td>0.2612</td>
<td>0.1874</td>
<td>0.6420</td>
<td>0.1706</td>
<td>77.13</td>
</tr>
<tr>
<td>0.8</td>
<td>0.0500</td>
<td>0.6797</td>
<td>0.2703</td>
<td>0.1556</td>
<td>0.6651</td>
<td>0.1793</td>
<td>77.98</td>
</tr>
<tr>
<td>0.9</td>
<td>0.0395</td>
<td>0.6811</td>
<td>0.2794</td>
<td>0.1272</td>
<td>0.6851</td>
<td>0.1877</td>
<td>78.74</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0307</td>
<td>0.6807</td>
<td>0.2886</td>
<td>0.1019</td>
<td>0.7020</td>
<td>0.1961</td>
<td>79.42</td>
</tr>
</tbody>
</table>

11.7  
The solution to this exercise is given in detail by Widagdo and Seider in Ref. 19 of Chapter 11.

11.9  

**Extractive distillation column:**
A suitable design is as follows, but other designs are possible:
- 57 equilibrium stages, including the condenser and reboiler
- Solvent enters stage 12 from the top
- Feed enters stage 36 from the top
- Reflux ratio = 5
- Solvent flow rate = 70 mol/s
- Bottoms flow rate = 78.774 mol/s
- Column diameter = 7 ft
- Total pressure drop = 5.2 psi

**Ordinary distillation column:**
A suitable design is as follows, but other designs are possible:
- 39 equilibrium stages, including the condenser and reboiler
- Feed enters stage 25 from the top
- Reflux ratio = 15
- Column diameter = 6.5 ft
11.11 Because the feed is close to the azeotropic composition of 22 mol% methanol, use a two-column system, with the first column being extractive distillation and the second ordinary distillation to recover the solvent. UNIFAC for \( K \)-values. Negligible tray pressure drop. 100% tray efficiency.

UNIFAC predicts, at 1 atm, that toluene forms a minimum-boiling azeotrope with methanol at 63.8°C, with a mole fraction of methanol equal to 0.891. Thus, toluene is a questionable solvent for extractive distillation because on a residue curve map for 1 atm pressure, a distillation boundary connects the acetone-methanol azeotrope with the methanol-toluene azeotrope, similar to Fig. 11.5, where a distillation boundary connects the benzene-isopropanol azeotrope with the benzene-n-propanol azeotrope. For extractive distillation, a residue curve map similar to that in Fig. 11.14 is needed.

11.13 Use the two-column system of Fig. 11.23b.

In Column 1, the pressures are 26 kPa at the condenser outlet, 30 kPa at the top tray, and 40 kPa at the reboiler. The distillate product is the near azeotrope at 30 kPa and the bottoms product is 99 mol% ethanol.

In Column 2, the pressures are 106 kPa before the condenser, 101.3 kPa after the condenser, and 120 kPa at the reboiler. The distillate product is the near azeotrope at 101.3 kPa and the bottoms product is 99 mol% benzene.

Azeotrope compositions in mol% ethanol are 35.7 at 26 kPa, and 45.2 at 101.3 kPa.
A reasonable recycle ratio, \( D_2/F = 2.309 \), giving \( D_2 = 230.9 \) mol/s
The material balance is:

<table>
<thead>
<tr>
<th>Stream:</th>
<th>( F )</th>
<th>( D_2 )</th>
<th>( F_1 )</th>
<th>( B_1 )</th>
<th>( D_1 )</th>
<th>( B_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>55</td>
<td>101.60</td>
<td>156.60</td>
<td>54.55</td>
<td>102.05</td>
<td>0.45</td>
</tr>
<tr>
<td>Benzene</td>
<td>45</td>
<td>129.30</td>
<td>174.30</td>
<td>0.55</td>
<td>173.75</td>
<td>44.45</td>
</tr>
<tr>
<td>Total:</td>
<td>100</td>
<td>230.90</td>
<td>330.90</td>
<td>55.10</td>
<td>275.80</td>
<td>44.90</td>
</tr>
<tr>
<td>mol% Ethanol:</td>
<td>55</td>
<td>44</td>
<td>47.33</td>
<td>99</td>
<td>37</td>
<td>1</td>
</tr>
</tbody>
</table>

**Column 1:** A possible design is as follows. Other designs are possible.

- 12 equilibrium stages, including condenser and reboiler
- Recycle enters stage 4 from the top
- Feed enters stage 6 from the top
- Reflux ratio = 0.28
- Column diameter = 12 feet

**Column 2:** A possible design is as follows. Other designs are possible.

- 6 equilibrium stages, including condenser and reboiler
- Feed to stage 2 from the top
- Reflux ratio = 0.16
- Column diameter = 9 ft
11.15 Use the two-column system of Fig. 11.23(b), except here the bottoms from Column 1 is nearly pure B (water), while the bottoms from Column 2 is nearly pure A (ethanol). Ethanol and water form a minimum-boiling azeotrope. For Column 1, set the pressures to 13 kPa at the condenser outlet, 15 kPa at the top tray, and 30 kPa at the reboiler. Specify a Column 1 distillate composition of 92.5 mol% ethanol compared to the predicted azeotropic composition of 94.3 mol%. Let the ethanol composition of the bottoms from Column 1 be 0.0001 mol% ethanol. For Column 2, set the pressures at 300 kPa at the condenser outlet, 305 kPa at the top tray, and 375 kPa at the reboiler. Specify a distillate composition of 88 mol% ethanol compared to the predicted azeotrope of 85.6 mol% ethanol. The bottoms from Column 2 is specified as 99.8 mol% ethanol. Recycle ratio = \( \frac{D_2}{F} = 0.4876 \) (modest). Therefore \( D_2 = 48.76 \text{ mol/s} \)

The material balance is:

<table>
<thead>
<tr>
<th>Stream</th>
<th>( F )</th>
<th>( D_2 )</th>
<th>( D_1 )</th>
<th>( B_1 )</th>
<th>( B_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate, mol/s:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>30</td>
<td>42.91</td>
<td>72.91</td>
<td>0.00007</td>
<td>72.91</td>
</tr>
<tr>
<td>Water</td>
<td>70</td>
<td>5.85</td>
<td>75.85</td>
<td>69.94</td>
<td>5.91</td>
</tr>
<tr>
<td>Total:</td>
<td>100</td>
<td>48.76</td>
<td>148.76</td>
<td>69.94</td>
<td>30.06</td>
</tr>
<tr>
<td>mol% Ethanol:</td>
<td>30</td>
<td>88</td>
<td>49.0</td>
<td>0.0001</td>
<td>92.5</td>
</tr>
</tbody>
</table>

For Column 1, use 42 stages (includes total condenser and partial reboiler) with 1st feed stage = 23 and 2nd feed stage = 35. Reflux ratio = 13.47. Column inside diameter = 24.5 feet for 30-inch tray spacing.

For Column 2, use 88 stages (includes total condenser and partial reboiler) with feed stage = 20. Reflux ratio = 7.34. Column inside diameter = 7.5 feet for 24-inch tray spacing.

11.17 For azeotropic column, use 31 stages (includes condenser and reboiler). Combined feed stage = 16 from the condenser. Reflux ratio = 3

The calculated material balance in mol/s is:

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Entrainer</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>50</td>
<td>0</td>
<td>0.3</td>
<td>49.7</td>
</tr>
<tr>
<td>2,5-DMH</td>
<td>50</td>
<td>0</td>
<td>49.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Methanol</td>
<td>0</td>
<td>192</td>
<td>191.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Total:</td>
<td>100</td>
<td>192</td>
<td>242.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

The resulting column inside diameter is determined to be 16 feet. The distillate azeotrope is separated by liquid-liquid extraction with water to give a methanol-water mixture that is separated by ordinary distillation to recover the methanol for recycle to the azeotropic tower, and water for recycle to the extraction section.

11.19 The preconcentration column is not needed. Unfortunately, repeated attempts to achieve nearly pure ethanol, using different combinations of entrainer flow rates and compositions were unsuccessful. The best ethanol purity achieved is 95 mol%. For that
case, 14 equilibrium stages are used in the azeotropic column plus a decanter-condenser combination and a partial reboiler, with the feed to stage 4 from the top. The entrainer recovery column has a reflux ratio of two and 15 stages, including a total condenser and a partial reboiler, with the feed to stage 5 from the condenser. The distillate from the third column and the benzene-rich liquid phase from the decanter are recycled to the top of the azeotropic column. Convergence of both the column calculations and the recycle streams is difficult. A reasonably converged material balance, keyed to the three-column diagram of Fig. 11.31 is as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Stream in Fig. 11.31a</th>
<th>D1</th>
<th>D3</th>
<th>L2</th>
<th>V2</th>
<th>B2</th>
<th>D2</th>
<th>B3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>15</td>
<td>11.4</td>
<td>3.8</td>
<td>23.3</td>
<td>6.9</td>
<td>19.5</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>0</td>
<td>20.0</td>
<td>88.8</td>
<td>108.8</td>
<td>0.2</td>
<td>20.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>135</td>
<td>46.2</td>
<td>25.7</td>
<td>71.9</td>
<td>135.0</td>
<td>46.3</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>150</td>
<td>77.6</td>
<td>118.3</td>
<td>204.0</td>
<td>142.1</td>
<td>85.8</td>
<td>8.2</td>
<td></td>
</tr>
</tbody>
</table>

11.21 Consider a separation sequence that omits the preconcentator column shown in Fig. 11.31 because the feed is already concentrated in water. The feed is sent directly into the heterogeneous azeotropic distillation column with a decanter to split the two liquid phases resulting from the condensation of the overhead vapor. The number of stages is 10, with the feed stage is stage 4 from the top. The material balance is as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Entrainer</th>
<th>Make-up</th>
<th>Bottoms</th>
<th>Overhead</th>
<th>Distillate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/o makeup</td>
<td>NPA</td>
<td>vapor</td>
<td>vapor</td>
<td>vapor</td>
<td>vapor</td>
</tr>
<tr>
<td>Water</td>
<td>800</td>
<td>184</td>
<td>0</td>
<td>1.3</td>
<td>982.7</td>
<td>798.4</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>200</td>
<td>58</td>
<td>0</td>
<td>183.6</td>
<td>74.4</td>
<td>16.0</td>
</tr>
<tr>
<td>NPA</td>
<td>0</td>
<td>760</td>
<td>3.6</td>
<td>0.1</td>
<td>763.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Total:</td>
<td>1000</td>
<td>1002</td>
<td>3.6</td>
<td>185.0</td>
<td>1820.6</td>
<td>817.9</td>
</tr>
</tbody>
</table>

The acetic acid product is 99.2 mol% acetic acid, while the bottoms water product is 97.6 mol% water. This could be further purified in a second column, with the small amount of acetic acid-rich product recycled.
11.23 Kinetic data is given in Example 11.9, but substitute activities for mole fractions in the kinetic equations. The activity = activity coefficient times the mole fraction. Use the UNIQUAC equation for activity coefficients. With Aspen Plus, built-in kinetic rate-law expressions are not available in terms of activities. Therefore, a FORTRAN subroutine for the rate-law must be provided. For methanol fed to stage 10, the conversion of isobutene, when using activities, is 99.5% compared to a 95.6% conversion in Example 11.9, when mole fractions are used.

11.25 The results are almost identical to those for Example 11.10, using just 5 equilibrium stages. This should not be surprising! Supercritical extraction is analogous to stripping or liquid-liquid extraction. Thus, an approximate calculation made with the Kremser method based on stripping factors for ethanol and water, and an absorption factor for carbon dioxide predicts little effect of the number of stages above 5.
Chapter 12

12.1

Let $\phi_j$ = ratio of entrained liquid (in the exiting vapor) that leaves Stage $j$ to the liquid leaving Stage $j$ and $\theta_j$ = ratio of occluded vapor (in the exiting liquid) that leaves Stage $j$ to the vapor leaving Stage $j$.

$$M_{i,j}^L \equiv (1 + r_j^L + \phi_j) L_j x_{i,j} - L_{j-1} x_{i,j-1} - \phi_{j+1}(1 + r_{j+1}^L) L_{j+1} x_{i,j+1} - f_{i,j}^L - N_{i,j}^L = 0, \quad i = 1, 2, \ldots, C$$

$$M_{i,j}^V \equiv (1 + r_j^V + \theta_j) V_j y_{i,j} - V_{j-1} y_{i,j-1} - \theta_{j-1}(1 + r_{j-1}^V) V_{j-1} y_{i,j-1} - f_{i,j}^V + N_{i,j}^V = 0, \quad i = 1, 2, \ldots, C$$

$$E_j^L \equiv (1 + r_j^L + \phi_j) L_j H_j^L - L_{j-1} H_{j-1}^L - \phi_{j+1}(1 + r_{j+1}^L) L_{j+1} H_{j+1}^L$$

$$- H_j^L \sum_{i=1}^C f_{i,j}^L + Q_j - e_j^L = 0$$

$$E_j^V \equiv (1 + r_j^V + \theta_j) V_j H_j^V - V_{j+1} H_{j+1}^V - \theta_{j-1}(1 + r_{j-1}^V) V_{j-1} H_{j-1}^V - H_j^V \sum_{i=1}^C f_{i,j}^V + Q_j + e_j^V = 0$$

$$M_{T,j}^L \equiv (1 + r_j^L + \phi_j) L_j - L_{j-1} - \phi_{j+1}(1 + r_{j+1}^L) L_{j+1} - \sum_{i=1}^C f_{i,j}^L - N_{T,j} = 0$$

$$M_{T,j}^V \equiv (1 + r_j^V + \theta_j) V_j - V_{j+1} - \theta_{j-1}(1 + r_{j-1}^V) V_{j-1} - \sum_{i=1}^C f_{i,j}^V + N_{T,j} = 0$$

12.3

The equations can be rewritten to replace:

$x_{i,j}, y_{i,j}, L_j,$ and $V_j$ by $l_{i,j}$ and $v_{i,j}$ to give $(5C + 3)$ variables instead of $(5C+5)$ variables.

This has the advantage that the component material balances are linear and less equations are needed because there are two fewer variables per stage. However, the use of mole fractions and total flow rates is preferable when taking into account entrainment, occlusion, backmixing, weeping, and tray hydraulics.

The percentage reduction in the number of variables and equations for the rate-based model is not nearly as great as for the equilibrium model because, at least not for many components, that number is dominated by the $5C$ term.
The separation achieved is:

<table>
<thead>
<tr>
<th>Component</th>
<th>2 Feeds</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow, kmol/h:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetone</td>
<td>50.0</td>
<td>47.59</td>
<td>2.41</td>
</tr>
<tr>
<td>Methanol</td>
<td>150.0</td>
<td>0.20</td>
<td>149.80</td>
</tr>
<tr>
<td>Water</td>
<td>50.0</td>
<td>2.20</td>
<td>47.80</td>
</tr>
<tr>
<td>Total:</td>
<td>250.0</td>
<td>49.99</td>
<td>200.01</td>
</tr>
</tbody>
</table>

| Mole fraction: |       |            |         |
| Acetone       | 0.200  | 0.9519     | 0.0120  |
| Methanol      | 0.6000 | 0.0040     | 0.7490  |
| Water         | 0.2000 | 0.0441     | 0.2390  |

Need 30 equilibrium stages plus total condenser and partial reboiler.
12.13

The separation achieved is:

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow, kmol/h:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>100.0</td>
<td>90.09</td>
<td>8.91</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>50.0</td>
<td>8.89</td>
<td>41.11</td>
</tr>
<tr>
<td>Water</td>
<td>100.0</td>
<td>0.02</td>
<td>99.98</td>
</tr>
<tr>
<td>Total:</td>
<td>250.0</td>
<td>100.00</td>
<td>150.00</td>
</tr>
</tbody>
</table>

Mole fraction:

<table>
<thead>
<tr>
<th>Component</th>
<th>Methanol</th>
<th>Isopropanol</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mole fraction</td>
<td>0.4000</td>
<td>0.2000</td>
<td>0.4000</td>
</tr>
</tbody>
</table>

12.15

The peak efficiency is achieved in the neighborhood of 50% flooding, but the separation is little affected over the range of 25 to 85% of flooding.

At 85% of flooding, the separation achieved is:

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed to tray 1</th>
<th>Feed to tray 12</th>
<th>Vapor Distillate</th>
<th>Vapor bottoms</th>
<th>Liquid bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>1320</td>
<td>1094</td>
<td>2398.83</td>
<td>12.95</td>
<td>2.22</td>
</tr>
<tr>
<td>Argon</td>
<td>5</td>
<td>27</td>
<td>10.36</td>
<td>12.69</td>
<td>8.95</td>
</tr>
<tr>
<td>Oxygen</td>
<td>24</td>
<td>711</td>
<td>77.81</td>
<td>321.36</td>
<td>335.83</td>
</tr>
<tr>
<td>Total:</td>
<td>1349</td>
<td>1832</td>
<td>2487.00</td>
<td>347.00</td>
<td>347.00</td>
</tr>
</tbody>
</table>

12.17

(a) For 40% absorption of propane, need 15 equilibrium stages. Separation is:

Flow rate, kmol/s:

<table>
<thead>
<tr>
<th>Component</th>
<th>Absorber oil</th>
<th>Rich gas</th>
<th>Lean gas</th>
<th>Rich oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>0.00</td>
<td>3.146</td>
<td>3.050</td>
<td>0.096</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.00</td>
<td>1.727</td>
<td>1.503</td>
<td>0.224</td>
</tr>
<tr>
<td>Propane</td>
<td>0.00</td>
<td>2.640</td>
<td>1.618</td>
<td>1.022</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.22</td>
<td>1.859</td>
<td>0.121</td>
<td>1.958</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>0.55</td>
<td>1.628</td>
<td>0.084</td>
<td>2.094</td>
</tr>
<tr>
<td>n-Dodecane</td>
<td>10.23</td>
<td>0.000</td>
<td>0.001</td>
<td>10.229</td>
</tr>
<tr>
<td>Total</td>
<td>11.00</td>
<td>11.000</td>
<td>6.377</td>
<td>15.623</td>
</tr>
</tbody>
</table>
12.17 (continued)

(b) Using 20 actual trays, the separation achieved is:

<table>
<thead>
<tr>
<th>Component</th>
<th>Absorber oil</th>
<th>Rich gas</th>
<th>Lean gas</th>
<th>Rich oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>0.00</td>
<td>3.146</td>
<td>3.050</td>
<td>0.096</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.00</td>
<td>1.727</td>
<td>1.501</td>
<td>0.226</td>
</tr>
<tr>
<td>Propane</td>
<td>0.00</td>
<td>2.640</td>
<td>1.605</td>
<td>1.035</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.22</td>
<td>1.859</td>
<td>0.120</td>
<td>1.959</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>0.55</td>
<td>1.628</td>
<td>0.081</td>
<td>2.097</td>
</tr>
<tr>
<td>n-Dodecane</td>
<td>10.23</td>
<td>0.000</td>
<td>0.001</td>
<td>10.229</td>
</tr>
<tr>
<td>Total</td>
<td>11.00</td>
<td>11.000</td>
<td>6.358</td>
<td>15.642</td>
</tr>
</tbody>
</table>

The back-calculated Murphree vapor tray efficiencies are mainly in the following ranges:
- Methane: 54 to 80%
- Ethane: 55 to 75%
- Propane: 46 to 77%
- n-Butane: 65 to 77%
- n-Pentane: 74 to 80%
- n-Dodecane: 73 to 78%

12.19

Use 23 m above the feed and 4 m below the feed. Separation is:

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow, kmol/h</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>93.11</td>
<td>89.28</td>
<td>3.84</td>
</tr>
<tr>
<td>Ethanol</td>
<td>5.00</td>
<td>3.82</td>
<td>1.18</td>
</tr>
<tr>
<td>Water</td>
<td>44.35</td>
<td>0.01</td>
<td>44.34</td>
</tr>
<tr>
<td>Total</td>
<td>142.46</td>
<td>93.10</td>
<td>49.36</td>
</tr>
</tbody>
</table>

Mole fraction:
- Methanol: 0.6536, 0.9589, 0.0777
- Ethanol: 0.0351, 0.0410, 0.0240
- Water: 0.3113, 0.0001, 0.8983
Chapter 13

13.1  (a) At 50 wt% distilled:

    residue = 46.145 lb
    mass fraction of C7 in residue = 0.0110
    mass fraction of C7 in cumulative distillate = 0.0324

(b) At 50% of the C7 distilled:

    mole fraction of C7 in residue = 0.0142
    mass fraction of C7 in cumulative distillate = 0.0365
    wt% of charge distilled = 29.9

13.3  Moles of residue = 57.9

13.5

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Moles distillate/mole feed</td>
<td>0.73</td>
<td>0.40</td>
<td>0.485</td>
</tr>
<tr>
<td>(b) Mole fraction of benzene in distillate</td>
<td>0.700</td>
<td>0.75</td>
<td>0.742</td>
</tr>
<tr>
<td>Mole fraction of benzene in residue</td>
<td>0.330</td>
<td>0.50</td>
<td>0.466</td>
</tr>
</tbody>
</table>

13.7  Time = 2.14 h

13.9  Mole fraction of isopropanol in residue = 0

13.11 0.548 kmol distilled

13.13 (a) Number of equilibrium stages = between 8 and 9

(b)

<table>
<thead>
<tr>
<th>$R/L/D$</th>
<th>2.33</th>
<th>3.0</th>
<th>4.0</th>
<th>5.67</th>
<th>9.0</th>
<th>19</th>
<th>infinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{W}$</td>
<td>0.48</td>
<td>0.35</td>
<td>0.22</td>
<td>0.13</td>
<td>0.065</td>
<td>0.035</td>
<td>0.006</td>
</tr>
<tr>
<td>$W/W_0$</td>
<td>0.95</td>
<td>0.73</td>
<td>0.59</td>
<td>0.52</td>
<td>0.48</td>
<td>0.46</td>
<td>0.45</td>
</tr>
</tbody>
</table>

(c) Total vapor generated = 160 kmol/a00 kmol of initial charge

Case of constant distillate composition requires more energy.

Might be more efficient to start with constant distillate composition with a
switch to constant reflux ratio when that ratio becomes 2.2.
13.15 (a) Time for operation step 1 = 7.28 h
(b) kmol of cumulative distillate = 200 kmol
(c) Minimum reflux ratio = 2.35, Maximum reflux ratio = 3.7
(d) Variation of distillate rate:

<table>
<thead>
<tr>
<th>Time, h</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>7.28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distillate, kmol/h</td>
<td>29.9</td>
<td>28.6</td>
<td>26.9</td>
<td>24.1</td>
<td>21.3</td>
</tr>
</tbody>
</table>

13.23 Mole fraction of nC6 in distillate = 0.695

13.25

<table>
<thead>
<tr>
<th>Time, h</th>
<th>(x_W)_A</th>
<th>(x_W)_B</th>
<th>(x_D)_A</th>
<th>(x_D)_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.4000</td>
<td>0.5000</td>
<td>0.6368</td>
<td>0.3433</td>
</tr>
<tr>
<td>0.2</td>
<td>0.3979</td>
<td>0.5014</td>
<td>0.6155</td>
<td>0.3600</td>
</tr>
<tr>
<td>0.4</td>
<td>0.3959</td>
<td>0.5027</td>
<td>0.6136</td>
<td>0.3617</td>
</tr>
<tr>
<td>0.6</td>
<td>0.3939</td>
<td>0.5040</td>
<td>0.6117</td>
<td>0.3634</td>
</tr>
<tr>
<td>0.8</td>
<td>0.3919</td>
<td>0.5053</td>
<td>0.6097</td>
<td>0.3651</td>
</tr>
<tr>
<td>1.0</td>
<td>0.3989</td>
<td>0.5066</td>
<td>0.6077</td>
<td>0.3668</td>
</tr>
</tbody>
</table>

13.27 (a) Time for rectification = 22.8 h
(b) Total amount of distillates produced = 50.6 lbmol

13.29

<table>
<thead>
<tr>
<th>Cut</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mole fraction:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>0.923</td>
<td>0.077</td>
<td>0.000</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.077</td>
<td>0.871</td>
<td>0.039</td>
</tr>
<tr>
<td>n-Propanol</td>
<td>0.000</td>
<td>0.052</td>
<td>0.961</td>
</tr>
<tr>
<td>kmol</td>
<td>30</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

13.31

<table>
<thead>
<tr>
<th>Cut</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mole fraction:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetone</td>
<td>0.967</td>
<td>0.398</td>
<td>0.001</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.016</td>
<td>0.043</td>
<td>0.901</td>
</tr>
<tr>
<td>Chloroform</td>
<td>0.017</td>
<td>0.559</td>
<td>0.098</td>
</tr>
<tr>
<td>kmol</td>
<td>26.6</td>
<td>48.4</td>
<td>25.0</td>
</tr>
</tbody>
</table>
Chapter 14

14.3 Membrane area = 48,800 m²
   Methane flow rate in the permeate = 281 kmol/h

14.5 Spacing between turns = 2 mm

14.7 Flow rate of water = 41,700 m³/m²-day

14.9

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole fraction in Permeate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>0.019</td>
</tr>
<tr>
<td>Methane</td>
<td>0.010</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.028</td>
</tr>
<tr>
<td>Propane</td>
<td>0.091</td>
</tr>
<tr>
<td>n-butane</td>
<td>0.852</td>
</tr>
</tbody>
</table>

14.11 Case 1: Membrane areas are 195 m² for each stage.
   Permeate product = 60 lbmol/h with a C3= mole fraction = 0.761
Case 2: Membrane areas are 255 and 94 m².
   Permeate product = 60 lbmol/h with a C3= mole fraction = 0.761

14.13 Membrane area = 545 m²
   65% recovery of sodium sulfate to the diffusate

14.15 Current density = 73 amp/m²
   Current = 25.6 amp
   Power for first stage = 5.6 kW

14.17 For Design 2, % recovery = 75%
   For Design 3, % recovery = 87.5%

14.19 Membrane area = 550,000 ft² to achieve a retentate with 0.05 mol% acetone

14.21 For crossflow, membrane area = 197,000 ft² for a feed rate = 10,000 scfm

14.23 Permeance for ethyl alcohol = 4.62 x 10⁻⁵ kmol/h-m²-mm Hg
   Permeance for water = 6.23 x 10⁻⁴ kmol/h-m²-mm Hg
### Component material balance in lb/day of operation:

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Feed</th>
<th>Stage 1 Conc.</th>
<th>Stage 2 Conc.</th>
<th>% Overall Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>6,000</td>
<td>5,733</td>
<td>4,874</td>
<td>81.2</td>
</tr>
<tr>
<td>NPN</td>
<td>3,000</td>
<td>1,464</td>
<td>293</td>
<td>9.8</td>
</tr>
<tr>
<td>Lactose</td>
<td>49,000</td>
<td>20,327</td>
<td>3,183</td>
<td>6.5</td>
</tr>
<tr>
<td>Ash</td>
<td>8,000</td>
<td>3,384</td>
<td>545</td>
<td>6.8</td>
</tr>
<tr>
<td>B fat</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>100.0</td>
</tr>
<tr>
<td>Water</td>
<td>933,500</td>
<td>362,064</td>
<td>47,741</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,000,000</td>
<td>393,472</td>
<td>57,136</td>
<td></td>
</tr>
</tbody>
</table>

The number of cartridges = 141/stage or 282 total.

### Stage 1:
- Permeate flux = 0.58 mL/min-cm²
- Permeate volume at 18.8 min = 188 mL

### Stage 2:
- Permeate flux drops to 0.28 mL/min-cm² at 47.5 min
- Permeate volume total = 380 mL
Chapter 15

15.1 (a) 0.369 cm$^3$/g  
(b) 2.50 g/cm$^3$  
(c) 47.6 angstroms

15.3 (a) Yes, values are reasonable.  
(b) 79% if capacity is on the dry basis,  
or 87% if capacity is assumed on the wet basis.

15.5 5.35 meq/g of resin

15.7 (a) Propylene  
(b) Activated carbon  
(c) Zeolite ZMS 4A  
(d) Zeolite ZMS 4A

15.9 (a) Using linear regression with Excel on the linearized equations:  
Propylene:  
Freundlich equation:  
\[ q = 0.01062p^{0.7626} \]  
Langmuir equation:  
\[ q = \frac{0.00185(2.52)p}{1+0.00185p} \]

Propylene:  
Freundlich equation:  
\[ q = 0.06242p^{0.5463} \]  
Langmuir equation:  
\[ q = \frac{0.00392(2.82)p}{1+0.00392p} \]

None of the fits are entirely satisfactory.  
Langmuir is best.  
Propylene is more strongly adsorbed.

(b) For the extended Langmuir isotherm:

Propane:
\[
q_{C3} = \frac{(q_{C3})_m K_{C3} p_{C3}}{1+K_{C3} p_{C3} + K_{C3=} p_{C3=}}
\]
\[
= \frac{2.5213(0.001853)p_{C3}}{1+0.001853p_{C3} + 0.003916p_{C3=}}
\]

Propylene:
\[
q_{C3=} = \frac{(q_{C3=})_m K_{C3=} p_{C3=}}{1+K_{C3=} p_{C3} + K_{C3=} p_{C3=}}
\]
\[
= \frac{2.8201(0.003916)p_{C3=}}{1+0.001853p_{C3} + 0.003916p_{C3=}}
\]

(c) Very difficult to fit multicomponent data to extended Langmuir  
Many fits give about the same degree of goodness of fit.  
One fit is:
\[
(q_{C3})_m = 2.153, \quad (q_{C3=})_m = 4.042, \quad K_{C3} = 0.001642, \quad \text{and } K_{C3=} = 0.001997 \]
(d) Very difficult to fit multicomponent data to extended Freundlich. Many fits give about the same degree of goodness of fit. One fit is:

\[
(q_{C3})_m = 1.706, \\
(q_{C3^=})_m = 4.507, \\
K_{C3} = 0.0270, \\
K_{C3^=} = 0.03773, \\
n_{C3} = 1.59, \\
\text{and } n_{C3^=} = 1.90
\]

(e) The relative selectivity varies widely

15.13 (a) 
\[
\text{SO}_4^{2-} + 2\text{Cl}^- \text{R}_{(s)} \leftrightarrow \text{SO}_4\text{R}_{2(s)} + 2\text{Cl}^-_{(l)}
\]
(b) 0.15
(c) 
\[
c_{\text{SO}_4} = 0.00542 \text{ eq/L} \\
c_{\text{Cl}^-} = 0.01458 \text{ eq/L} \\
q_{\text{SO}_4} = 0.754 \text{ eq/L} \\
q_{\text{Cl}^-} = 0.445 \text{ eq/L}
\]
(d) 1.829 eq/L
(e) 
\[
c_{\text{SO}_4} = 0.0191 \text{ eq/L} \\
c_{\text{Cl}^-} = 1.810 \text{ eq/L} \\
q_{\text{SO}_4} = 0.00123 \text{ eq/L} \\
q_{\text{Cl}^-} = 1.199 \text{ eq/L}
\]
(f) The regeneration step is more selective than the ion-exchange step.

15.15 Need 4,170 kg dry resin

15.17 Mass-transfer coefficient 
\[
= 0.0392 \text{ m/s}
\]
Heat-transfer coefficient
\[
= 280 \text{ J/s-m}^2-\text{K}
\]

15.19 Effective diffusivity
\[
= 0.0054 \text{ cm}^2/\text{s}
\]
Surface diffusion very important.

15.21 (a) 0.66 g carbon/L solution
(b) 12.2 h
(c) 39 days
(d) 48,000 kg

15.23 (a) 0.286 g carbon/L of solution
(b) 14.3 h
(c) 5.4 days
(d) Need extremely large vessel

15.25 Every 279 days

15.27 84 cannisters per month
Monthly cost = $58,800

15.29 Desorption time almost 250 min.

15.35 (a) 3,219 L/min
(b) 26.6 h
(c) 0.191 cm/min
(d) 322 L/min
(e) 19 min

15.37 Pulse = 165 s, followed by elute = 2,732 s, etc.
### 15.39

<table>
<thead>
<tr>
<th></th>
<th>Fructose</th>
<th>Glucose</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extract, MTC = 10 min⁻¹</td>
<td>211.6</td>
<td>8.4</td>
<td>861.7</td>
</tr>
<tr>
<td>Extract, MTC = 1,000 min⁻¹</td>
<td>223.2</td>
<td>2.6</td>
<td>858.9</td>
</tr>
<tr>
<td>Raffinate, MTC = 10 min⁻¹</td>
<td>12.7</td>
<td>295.3</td>
<td>795.8</td>
</tr>
<tr>
<td>Raffinate, MTC = 1,000 min⁻¹</td>
<td>3.9</td>
<td>303.3</td>
<td>796.1</td>
</tr>
</tbody>
</table>
Chapter 16

16.1  Mass balance summary in lb/h:

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Solvent</th>
<th>Wet, leached solids</th>
<th>Extract</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>0.680</td>
<td>0.000</td>
<td>0.680</td>
<td>0.000</td>
</tr>
<tr>
<td>Oil</td>
<td>1.202</td>
<td>0.000</td>
<td>0.068</td>
<td>1.134</td>
</tr>
<tr>
<td>n-Hexane</td>
<td>0.000</td>
<td>10.844</td>
<td>4.654</td>
<td>6.190</td>
</tr>
<tr>
<td>Dry, oil and solvent-free flakes</td>
<td>4.493</td>
<td>0.000</td>
<td>4.493</td>
<td>0.000</td>
</tr>
</tbody>
</table>

This balance is an excellent check on the data given.

Mass ratio of oil to wet, leached solids = 0.0069

16.3  % recovery of NaOH in final overflow = 93.48%
Wt% NaOH in dried CaCO₃ = 0.191%
The use of 3 stages does not significantly increase the recovery of NaOH.

16.5  (a) 88.54%
(b) 76.6%

16.7  (a) 1 leaching stage + 3 washing stages
(b) 1 leaching stage + 2 washing stages

16.11  1.63 x 10⁻⁵ cm²/s

16.13

<table>
<thead>
<tr>
<th>Particle diameter, cm</th>
<th>0.05</th>
<th>0.5</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time, seconds</td>
<td>193</td>
<td>19,300</td>
<td>1,930,000</td>
</tr>
</tbody>
</table>

16.15  Leaching time = 17.9 h
Chapter 17

17.1  (a) 0.696  
      (b) 0.727

17.5  Surface-mean diameter = 0.579 mm  
      Mass-mean diameter = 0.911 mm  
      Arith.-mean diameter = 0.132 mm  
      Volume-mean diameter = 0.272 mm

17.7  Surface-mean diameter = 0.570 mm  
      Mass-mean diameter = 0.633 mm  
      Arith.-mean diameter = 0.431 mm  
      Volume-mean diameter = 0.498 mm

17.9  1,442 lb/h of crystals

17.11 Evaporation rate = 1,490 lb/h  
      Crystals rate = 44.6 tons/day

17.13 Temperature out = 257°F

17.15 Heat removal rate  
      = 20,180 cal/100 g feed water

17.17 Supersaturation ratio = 1.007

17.19

<table>
<thead>
<tr>
<th>Comp.</th>
<th>$S = 1.02$</th>
<th>$S = 1.005$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgNO₃</td>
<td>$4.37 \times 10^{25}$</td>
<td>$1.91 \times 10^{39}$</td>
</tr>
<tr>
<td>NaNO₃</td>
<td>$1.33 \times 10^{29}$</td>
<td>$1.54 \times 10^{16}$</td>
</tr>
<tr>
<td>KNO₃</td>
<td>$4.20 \times 10^{18}$</td>
<td>$4.50 \times 10^{15}$</td>
</tr>
</tbody>
</table>

17.21 Crystal growth rate is controlled by  
surface reaction, with a small  
contribution from mass-transfer.

17.23  (a) 4.84 tons/h  
        (b) 1,270 ft²  
        (c) 43 units

17.25  (a) 1.249 kg/h  
        (b) 3,151 kg/h  
        (c) 4.96 m³

17.27  (a) $2.64 \times 10^{11}$  
        (b) 0.0647 micron/s  
        (c) $1.71 \times 10^{10}$ nuclei/L-s  
        (d) 2.46 microns  
        (e) $6.49 \times 10^{11}$ crystals/L  
        (f) Results are consistent  
        (g) 0.053 micron/s

17.29  (a) 0.047 micron/min  
        (b) 44 nuclei/L-min  
        (c) 0.705 micron

17.31 The para isomer will  
crystallize.  
Time = 1.17 h

17.35

<table>
<thead>
<tr>
<th>$z/l$</th>
<th>$w_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0058</td>
</tr>
<tr>
<td>2</td>
<td>0.0120</td>
</tr>
<tr>
<td>4</td>
<td>0.0155</td>
</tr>
<tr>
<td>6</td>
<td>0.0175</td>
</tr>
<tr>
<td>8</td>
<td>0.0186</td>
</tr>
<tr>
<td>9</td>
<td>0.0190</td>
</tr>
</tbody>
</table>

Avg. concentration = 0.0138

17.37 Final gas temperature =  
101°C  
Fractional yield = 93%
17.39  (a) 44°F
      (b) 206°F and 13 psia
      (c) 25,000 lb/h
      (d) 28,400,000 Btu/h
      (e) 29,100 lb/h
      (f) 85.9%
      (g) 2,370 ft²

17.41  (a) 7 psia
      (b) 49.5%
      (c) 330 ft²
      (d) 153%
Chapter 18

18.15  (a) 0.0158 lb water/lb dry air  
       (b) 0.0254 mol water/mol dry air 
       (c) Not applicable  
       (d) 1.22%  
       (e) Not applicable  
       (f) 18.3 ft³/lb dry air  
       (g) 0.247 Btu/lb dry air°F  
       (h) 70.8 Btu/lb dry air  
       (i) 105°F  
       (j) 0.0248

18.17  (a) 0.048 mol water/mol dry air  
       (b) 0.072 lb water/lb dry air  
       (c) 44.3%  
       (d) 41.7%  
       (e) 10.4 ft³/lb dry air  
       (f) \( c_s = 0.254 \text{ Btu/lb dry air°F} \)  
       \( H = 57.4 \text{ Btu/lb dry air} \)

18.19  Humidity = 0.21 lb toluene/lb dry air  
       \( T_s = 112°F \)  
       \( T_w = 118°F \)

18.21  (a) 151°F  
       (b) 141°F  
       (c) 158°F

18.25  (a) 0.194 lb water/lb dry lumber  
       (b) 0.306 lb water/lb dry lumber  
       (c) 0.425 lb water/lb dry lumber  
       (d) 0.425 lb water/lb dry lumber

18.27  (a) 2,160 lb  
       (b) 32.2 h  
       (c) 37.7 h  
       (d) 70.9 h

18.29  (a) 2 min.  
       (b) 9.2 min.

18.31  530 min.

18.33  (a) 96.8 wt%  
       (b) 0.0281 g water/h-cm²  
       (c) \( 1.8 \times 10^{-6} \text{ cm}^2/\text{s} \)  
       (d) Not parabolic

18.37  (a) 1,360 lb dry air/lb coffee  
       (b) 120°F  
       (c) 832 Btu/lb coffee solution

18.39  (a) 1,429 lb/h  
       (b) 1,664,000 Btu/h  
       (c) 1,782 lb/h

18.41  Final avg. moisture content  
       = 0.181 lb water/lb dry solid

18.43  Dryer diameter = 11.5 ft  
       Bead residence time = 450 s  
       Bed height = 0.32 ft  
       This is too small.  
       Steam rate = 33,900 kg/h  
       Heat-transfer rate  
       = 9,580,000 kJ/h
3. Problem-solving Techniques

The solution of separation problems may involve some of the following conversions or choices. With practice, a student should be able to make any of the following conversions or choices without reference to any book, notes, or other written material.

1. **Flow rate or amount:**
   For a continuous, steady-state process, mass, \( m \), molar, \( n \), or volumetric, \( Q \), flow rate, or average velocity, \( \bar{u} \), is used, which are related by the continuity equation:

\[
m = nM = Q\rho = \bar{u}A\rho
\]

where:

\( M = \text{average molecular weight} = \sum_i x_i M_i \)

mole fraction of species, \( i \)

\( A = \text{cross-sectional area for flow} \)

\( \rho = \text{mass density, which is inversely proportional to the molar volume, } \bar{u}, \text{ given by} \)

\[
\rho = \frac{M}{\bar{u}}
\]

For a batch process, the amount of material is used.

2. **Volumetric flow rate at standard conditions:**
   For gases, the flow rate is often given as standard cubic feet (SCF) per unit time, e.g. SCFM, SCFH, and SCFD, where standard conditions (S.C.) are 1 atm and 0°C or 60°F. To convert from these volumetric flow rates to molar flow rates, the following conversions are useful:

In the AE system of units,

\[
359 \text{ SCF/lbmol for S.C. of } 0^\circ\text{C (32°F)} \text{ and 1 atm}
\]

\[
379 \text{ SCF/lbmol for S.C. of } 60^\circ\text{F and 1 atm}
\]
In the SI system of units, 
\[22.4 \text{ m}^3/\text{kmol} \text{ for S.C. of } 0^\circ \text{C} (273 \text{ K}) \text{ and } 1 \text{ atm}\]

In the CGS system of units, 
\[22,400 \text{ cm}^3/\text{mol} \text{ for S.C. of } 0^\circ \text{C} \text{ and } 1 \text{ atm}\]

3. Mixture composition:

The composition of a mixture of components, \(i\), is most often expressed in terms of component mass flow rates, \(m_i\); molar flow rates, \(n_i\); mass fractions, \(\omega_i\); mole fractions, \(x_i\), \(y_i\), or \(z_i\); or molar concentrations, \(c_i\), which are related by:

\[m_i = n_iM_i = x_inM_i = \omega_im = c_iQM_i = x_i\frac{\rho}{M}QM_i\]

where,
\[c = \text{total molar concentration}\]

When the ideal gas law applies:

\[c = \frac{P}{RT} \text{ and } \rho = \frac{PM}{RT}\]

Where the most common values for \(R\) are:

- AE System: \(R = 0.7302 \text{ atm-ft}^3/\text{lbmol-oR}\)
- SI System: \(R = 8.315 \text{ kPa-m}^3/\text{kmol-K}\)
- CGS System: \(R = 82.06 \text{ atm-cm}^3/\text{mol-K}\)

For gases, when Dalton's law applies, composition can be expressed in terms of component partial pressures, \(p_i\):

\[p_i = y_iP\]

Compositions may also be given and/or used in terms of mass or mole ratios referred to some reference component, \(\text{ref}\), often one that does not undergo mass transfer from one phase to another to any appreciable extent:
\[ X_i = \frac{n_i}{n_{ref}} \quad \text{and} \quad \Omega_i = \frac{m_i}{m_{ref}} \]

4. **Volume fractions:**
   For an ideal gas, volume fractions are equal to mole fractions and are frequently used. For a liquid mixture, volume fractions are less useful, unless the liquid mixture is an ideal solution with zero volume of mixing. If so, then pure-component, liquid-phase densities can be used to compute volume fractions, \( \phi_i \):

\[
\phi_i = \frac{x_i \left( \frac{M_i}{\rho_i} \right)}{\sum_i x_i \left( \frac{M_i}{\rho_i} \right)} = \frac{x_i \left( \frac{M_i}{\rho_i} \right)}{\frac{M}{\rho}}
\]

5. **Parts per million:**
   Very small concentrations are frequently expressed in parts per million, ppm, or parts per billion, ppb. For solids and liquids, ppm or ppb is commonly understood to be by weight, whereas for gases, by mole or volume. However, it is advisable to be sure of the basis.

6. **Residence time and mixture composition in a vessel:**
   For a continuous flow, steady-state process, when mass transfer occurs in a vessel where the contents inside the vessel are assumed to be perfectly mixed, the composition of the mixture, in each phase in the vessel, is then equal to the composition of the corresponding phase in the effluent leaving the vessel (and not equal to the average of the feed to and effluent from the vessel). If the average residence time of the mixture in the vessel is sufficiently long and two or more phases co-exist, then the phases in the vessel and in the effluent approach phase equilibrium. The average residence time, \( t_{res} \) of the
mixture of all phases in the vessel, assuming it runs full, with a volume, \( V_{\text{vessel}} \), is:

\[ t_{\text{res}} = \frac{V_{\text{vessel}}}{Q} \]

7. **Fick's law of molecular diffusion:**
   
   When mass transfer of a component of a mixture occurs through a solid, or stagnant gas or liquid, Fick's law of molecular diffusion is used to determine the rate of mass transfer. The appropriate form of Fick's law depends on whether the flow is of a steady-state or unsteady-state nature. If the mass transfer is approximated by unimolecular diffusion, a correction for the bulk-flow effect is required. Ignoring this effect, Fick's first law for component, \( i \) is:

\[ n_i = N_i A = -D_i A \frac{dc_i}{dz} \]

where:
- \( N_i \) = the component flux
- \( D_i \) = the diffusivity
- \( A \) = the area for mass transfer
- \( z \) = the distance in the direction of mass transfer

8. **Mass-transfer coefficients:**
   
   When mass transfer occurs through a fluid in laminar or turbulent flow, mass-transfer rates are best calculated using mass-transfer coefficients obtained from appropriate correlations of experimental data, analogy to heat or momentum transport correlations, or theoretical derivations in the case of laminar flow. Equations based on mass-transfer coefficients may use driving forces based on any convenient composition variable. The particular driving force used determines the units of the mass-transfer coefficient. For example, if mass transfer is through a gas and a partial-pressure driving force is used, the equation for the rate of mass transfer, with no bulk-flow effect, is:

\[ n_i = k_{p_i} A (\Delta p_i) \]
For this case, the units of $k_{pi}$ in the SI system are,

$$\text{kmol/h-m}^2\cdot\text{kPa}$$

However, empirical correlations for mass-transfer coefficients, most often, are formulated for a mass-transfer rate with a concentration driving force,

$$n_i = k_{ci} A (\Delta c_i)$$

where the units of $k_{ci}$ in the SI system are,

$$\text{kmol/h-m}^2\cdot(\text{kmol/m}^3)$$

The most commonly used driving forces are $\Delta p_i$, $\Delta c_i$, $\Delta y_i$, and $\Delta x_i$, with coefficients $k_{pi}$, $k_{ci}$, $k_{yi}$, and $k_{xi}$, respectively. For an ideal gas and isothermal, isobaric conditions, the coefficients are related by:

$$k_{pi} = \frac{k_{ci}}{RT}$$

$$k_{yi} = \frac{k_{ci} P}{RT} = ck_{ci}$$

For a liquid, $k_{xi} = ck_{ci}$

9. **Models:**

A separation process is modeled by either an equilibrium-stage-based (thermodynamic) or a rate-based (mass transfer) model. For the former model, the separate phases leaving a stage are assumed to be perfectly mixed so that they each have a uniform composition that is in equilibrium with each other phase for each component, and have the same temperature and pressure. An equilibrium-stage model can be applied to all of the major separation processes except membrane
separations. For rate-based models, exiting phases are not each uniform in composition and temperature. However, they are assumed to be in equilibrium at the interface between two phases that contact each other. This is true for vapor-liquid interfaces as in distillation, absorption, and stripping; for liquid-liquid interfaces as in liquid-liquid extraction; and for fluid-solid interfaces as in adsorption, ion exchange, chromatography, leaching, drying, and with nonporous membranes. Phase equilibrium at an interface is analogous to the case of heat transfer where temperatures in two phases in contact are assumed to be equal at the phase interface. Phase equilibrium may or may not hold in crystallization and desublimation, where an interface resistance may be present because of the difficulty of solutes fitting into a crystalline lattice structure. This is somewhat analogous in heat transfer to contact resistance at the interface between two solid materials, which results in somewhat different temperatures for the two solids at the interface.

10. Material balance calculations:
A component material (mass) balance can be made with any of the composition variables cited in Item 3 above. For a balance around a chemical reactor, it is most convenient to use, as composition variables, component flow rates, related by the stoichiometric coefficients of the reactions. However, for a balance around a separator, the choice of composition variables (e.g. component flow rates, or component mole or mass fractions) depends upon the specifications for the degree of separation. Component recoveries favor use of component flow rates, while product purities favor use of component mole or mass fractions.
4. Suggestions for Completing
   Homework Exercises

1. Read the Exercise statement, noting the applicable section in the
   book, and whether the problem involves a continuous, steady-state process, a
   batch or other unsteady-state process, or some phenomenon not connected to
   a process.

2. Determine and state the subject of the exercise. For example, the
   subject of Exercise 3.2 might be stated as follows: The steady-state rate of
   evaporation of benzene from an open tank into air.

3. Determine what system of units might be best employed: SI, AE,
   or CGS, plus a choice of time unit (seconds, minutes, hours, etc).

4. Determine whether the Exercise is best solved with mass, mole, or
   volume flow rates or amounts. Determine how best to express mixture
   compositions (mass fraction, mole fraction, volume fraction, molar
   concentration, partial pressure if a gas, mass ratio, mole ratio, component
   flow rate or amount, etc.). Then convert the given quantities in the Exercise
   statement to your selection of flow rates, amounts, and/or compositions, in
   your selection of units.

5. Draw a schematic diagram of the process or phenomenon, showing
   given values, and state what is to be computed.

6. List all selected assumptions, for example, ideal gas law, Raoult's
   law, etc.

7. Write, develop, or refer to the applicable equations or principles,
   citing equation number(s) from the textbook, where possible. Always
   consider the applicability of the following types of equations:
   a. Total and/or component material balances in steady-
      state or transient form.
   b. Energy or enthalpy balances.
c. Phase equilibria equations for exiting streams or batches that are well mixed, or for equilibrium-phase interfaces.
d. Continuity equations for streams flowing through pipes or vessels to make conversions among average velocity, mass flow rate, mole flow rate, volumetric flow rate, and cross-sectional area for flow:

\[ m = nM = Q \rho = \bar{u}Ap \]
e. Mass-transfer rate equations:
   Fick's law of molecular diffusion in differential or finite-difference form for a solid or a stagnant fluid.
   Mass-transfer-coefficient form for laminar or turbulent flow.
f. Heat-transfer rate equations:
   Fourier's law of thermal conduction for a solid.
   Newton's law of cooling for a fluid.
g. Residence-time equations for well-mixed or plug-flow conditions.
h. Equations for estimating physical properties not given, citing equation numbers in the textbook, or a reference citation if property is taken from a handbook or computer program.
i. Any other types of equations for phenomena of interest.

8. Determine whether the equations can be solved graphically or analytically (preferably one-at-a-time). If they must be solved as a system and/or numerically, select a computer program to perform the calculation, e.g. a spreadsheet, Polymath, MathCAD, Maple, MATLAB, Mathematica, FORTRAN, C or C++ program, etc.

9. Carry out the computations, showing substitutions of quantities into equations.

10. Summarize the required results, using tables and/or graphs, when applicable and feasible.
11. Comment on the reasonableness and/or significance of your results.