

# Brief Contents

---

Chapter 1	Product Design Introduction	1
Chapter 2	Steps in Product-Development	32
<b>PART ONE</b>	<b>PRODUCT DESIGN FOR BASIC CHEMICALS</b>	<b>55</b>
Chapter 3	Materials Technology: Molecular-Structure Design for Basic Chemicals	61
Chapter 4	Process Synthesis—Basic Chemicals	77
Chapter 5	Process Simulation	110
Chapter 6	Process Synthesis Heuristics	152
Chapter 7	Design of Reactors and Reactor Networks	181
Chapter 8	Separation Train Synthesis	204
Chapter 9	Heat Exchanger Networks	252
Chapter 10	Mass Exchanger Networks	297
Chapter 11	Batch Process Design	309
Chapter 12	Plantwide Control	322
Chapter 13	Product Design Case Studies for Basic Chemicals	341
<b>PART TWO</b>	<b>PRODUCT DESIGN FOR INDUSTRIAL CHEMICALS</b>	<b>371</b>
Chapter 14	New Technologies for Industrial Chemical Products	375
Chapter 15	Product Design Case Studies for Industrial Chemicals	389
<b>PART THREE</b>	<b>PRODUCT DESIGN FOR CONFIGURED CONSUMER PRODUCTS</b>	<b>407</b>
Chapter 16	New Technologies for Configured Consumer Products	411
Chapter 17	Product Design Case Studies for Configured Consumer Products	442
<b>PART FOUR</b>	<b>DETAILED DESIGN, EQUIPMENT SIZING, OPTIMIZATION, AND PRODUCT-QUALITY ANALYSIS</b>	<b>467</b>
Chapter 18	Design of Heat Exchangers	469
Chapter 19	Design of Separation Towers	498
Chapter 20	Design of Pumps, Compressors, and Expanders	510
Chapter 21	Polymer Extrusion	518
Chapter 22	Cost Accounting and Capital Costs	534
Chapter 23	Manufacturing Costs and Profitability Analysis	602
Chapter 24	Optimization for Design	642
Chapter 25	Design for Six-Sigma	662
<b>PART FIVE</b>	<b>DESIGN REPORT</b>	<b>679</b>
Chapter 26	Written and Oral Reports	681
Appendix I	Heterogeneous Residue Curves	693
Appendix II	Design Problems	694
Appendix III	Materials of Construction	697
	Table of Acronyms	699
	Author Index	706
	Subject Index	711

# Contents

---

## Chapter 1

### Product Design Introduction 1

- 1.0 Objectives 1
- 1.1 Introduction 1
- 1.2 Product- and Technology-Development Framework 3
- 1.3 Innovation Map and Classes of Chemical Products 4
  - Innovation Map 4
  - Classes of Chemical Products 5
  - Basic Chemicals Innovation Maps 6
  - Industrial Chemicals Innovation Maps 7
  - Configured Consumer Chemical Product Innovation Maps 8
  - Literature Survey 10
  - Stimulating Invention and Innovation 12
  - Pharmaceutical Products 14
  - Socio-Technical Aspects of Product Design 15
- 1.4 Environmental Protection 16
  - Environmental Issues 17
  - Environmental Factors in Product and Process Design 19
  - Environmental Design Problems 20
- 1.5 Safety Considerations 21
  - Safety Issues 22
  - Design Approaches Toward Safe Chemical Plants 24
- 1.6 Engineering Ethics 24
- 1.7 Summary 30
- References 31

### 1S Supplement to Chapter 1

- 1S.1 HAZOP Analysis

## Chapter 2

### Steps in Product-Development 32

- 2.0 Objectives 32
- 2.1 Introduction 32
- 2.2 Project Charter and New Technologies 33
  - Project Charter 33
  - New Technologies 35
- 2.3 Stage-Gate™ Product-Development Process (SGPDP) 36
- 2.4 Concept Stage 36
  - Market Assessment 37
  - Customer Requirements 41

	Product Requirements	45
	Product Concepts	46
	Opportunity Assessments	48
2.5	Feasibility Stage	50
2.6	Development Stage	50
2.7	Manufacturing Stage	50
2.8	Product-Introduction Stage	51
	Henderson's Law	52
2.9	Summary	53
	References	53
	Exercises	54

## **PART ONE    PRODUCT DESIGN FOR BASIC CHEMICALS    55**

### **Chapter 3**

#### **Materials Technology: Molecular-Structure Design for Basic Chemicals    61**

3.0	Objectives	61
3.1	Introduction	62
3.2	Innovation Map for Environmentally Friendly Refrigerants	62
	Environmentally Friendly Refrigerant Inventions	62
	Innovation Map and Product Design for Environmentally Friendly Refrigerants	63
	Innovation Map	63
3.3	Searching for New Materials—Basic Chemical Products	64
	Pharmaceuticals Product Design	65
3.4	Property Estimation Methods	66
	Computer Data Banks	66
	Property Estimation	66
	Polymer Property Estimation	67
	Microsimulation	67
3.5	Optimization to Locate Molecular Structure	68
	Polymer Design	69
	Refrigerant Design	70
	Solvent Design	72
	Property Estimation	72
	Solvent Design for Crystallization of Organic Solids	75
	Solutes For Hand Warmers	75
3.6	Summary	75
	References	75
	Exercises	76

#### **3S Supplement to Chapter 3**

3S.1	Solvent Design for Crystallization of Organic Solids
3S.2	Solutes for Handwarmers

### **Chapter 4**

#### **Process Synthesis—Basic Chemicals    77**

4.0	Objectives	77
4.1	Introduction	77

4.2	Preliminary Database Creation	77
	Thermophysical Property Data	78
	Environmental and Safety Data	81
	Chemical Prices	81
	Summary	81
4.3	Experiments	81
4.4	Preliminary Process Synthesis	82
	Chemical State	82
	Process Operations	83
	Synthesis Steps	84
	Continuous or Batch Processing	85
	Example of Process Synthesis: Manufacture of Vinyl Chloride	85
	Synthesis Tree	93
	Heuristics	93
	Example of Process Synthesis: Manufacture of Tissue Plasminogen Activator (tPA)	94
	Synthesis Tree	101
	Algorithmic Methods	102
4.5	Development of the Base-Case Design	102
	Flow Diagrams	102
	Process Integration	106
	Detailed Database	106
	Pilot-Plant Testing	107
	Process Simulation	107
4.6	Summary	107
	References	108
	Exercises	108

## Chapter 5

### Process Simulation 110

5.0	Objectives	110
5.1	Introduction	111
5.2	Principles of Steady-State Flowsheet Simulation	111
	Process and Simulation Flowsheets	111
	Unit Subroutines	120
	Recycle	125
	Recycle Convergence Methods	129
	Flash with Recycle Problem	130
	Flash Vessel Control	131
	Equation-Oriented Architectures	131
5.3	Synthesis of the Toluene Hydrodealkylation Process	132
	Process Simulation	133
5.4	Steady-State Simulation of the Monochlorobenzene Separation Process	136
	Use of Process Simulators	136
5.5	Principles of Batch Flowsheet Simulation	138

	Process and Simulation Flowsheets	138
	Equipment Models	138
5.6	Summary	146
	References	147
	Exercises	147

**Chapter 6**

	<b>Process Synthesis Heuristics</b>	<b>152</b>
6.0	Objectives	152
6.1	Introduction	153
6.2	Raw Materials and Chemical Reactions	154
6.3	Distribution of Chemicals	154
	Inert Species	155
	Purge Streams	157
	Recycle to Extinction	159
	Selectivity	159
	Reactive Separations	160
	Optimal Conversion	161
6.4	Separations	161
	Separations Involving Liquid and Vapor Mixtures	161
	Separations Involving Solid Particles	162
6.5	Heat Removal from and Addition to Reactors	164
	Heat Removal from Exothermic Reactors	164
	Heat Addition to Endothermic Reactors	166
6.6	Heat Exchangers and Furnaces	167
6.7	Pumping, Compression, Pressure Reduction, Vacuum, and Conveying of Solids	168
	Increasing the Pressure	169
	Decreasing the Pressure	170
	Pumping a Liquid or Compressing a Gas	170
	Vacuum	171
	Conveying Granular Solids	172
	Changing the Pressure of Granular Solids	172
6.8	Changing the Particle Size of Solids and Size Separation of Particles	172
6.9	Removal of Particles from Gases and Liquids	173
6.10	Considerations That Apply to the Entire Flowsheet	173
6.11	Summary	173
	References	178
	Exercises	178

**Chapter 7**

	<b>Design of Reactors and Reactor Networks</b>	<b>181</b>
7.0	Objectives	181
7.1	Introduction	181
7.2	Reactor Models	182
	Reaction Stoichiometry	182
	Extent of Reaction	183
	Equilibrium	183
	Kinetics	185

	Ideal Kinetic Reaction Models—CSTRs and PFRs	185
7.3	Reactor Design for Complex Configurations	188
7.4	Reactor Network Design Using the Attainable Region	192
	Construction of the Attainable Region	192
	The Principle of Reaction Invariants	195
7.5	Rigorous Models for Tubular Chemical Reactors	197
	Isothermal Conditions	197
	Non-Isothermal Conditions	199
7.6	Supplemental Topics	200
7.7	Summary	200
	References	201
	Exercises	202

### **7S Supplement to Chapter 7**

7S.1	Locating the Separation Section with Respect to the Reactor Section
7S.2	Tradeoffs in Processes Involving Recycle
7S.3	Optimal Reactor Conversion
7S.4	Recycle to Extinction
7S.5	Snowball Effects in the Control of Processes Involving Recycle
7S.6	Computational Fluid Dynamics (CFD) Models for Tubular Chemical Reactors

## **Chapter 8**

### **Separation Train Synthesis 204**

8.0	Objectives	204
8.1	Introduction	204
	Feed Separation System	204
	Phase Separation of Reactor Effluent	205
	Industrial Separation Operations	209
8.2	Criteria for Selection of Separation Methods	211
	Phase Condition of the Feed as a Criterion	212
	Separation Factor as a Criterion	212
	Reason for the Separation as a Criterion	214
8.3	Selection of Equipment	214
	Absorption, Stripping, and Distillation	215
	Liquid–Liquid Extraction	215
	Membrane Separation	215
	Adsorption	215
	Leaching	215
	Crystallization	215
	Drying	215
8.4	Sequencing of Ordinary Distillation Columns for the Separation of Nearly Ideal Fluid Mixtures	216
	Column Pressure and Type of Condenser	216
	Number of Sequences of Ordinary Distillation Columns	216
	Heuristics for Determining Favorable Sequences	219

	Marginal Vapor Rate Method	219
	Complex and Thermally Coupled Distillation Columns	221
8.5	Sequencing of Operations for the Separation of Nonideal Fluid Mixtures	223
	Azeotropy	223
	Residue Curves	225
	Simple Distillation Boundaries	227
	Distillation Towers	227
	Distillation Lines	228
	Computing Azeotropes for Multicomponent Mixtures	229
	Distillation-Line Boundaries and Feasible Product Compositions	229
	Heterogeneous Distillation	230
	Multiple Steady States	233
	Pressure-Swing Distillation	233
	Membranes, Adsorbers, and Auxiliary Separators	236
	Reactive Distillation	236
	Separation Train Synthesis	237
8.6	Separation Systems for Gas Mixtures	242
	Membrane Separation by Gas Permeation	243
	Adsorption	243
	Absorption	244
	Partial Condensation and Cryogenic Distillation	244
8.7	Separation Sequencing for Solid–Fluid Systems	244
8.8	Summary	246
	References	246
	Exercises	248

## Chapter 9

### **Heat Exchanger Networks 252**

9.0	Objectives	252
9.1	Introduction	252
9.2	Minimum Utility Targets	254
	Temperature-Interval (TI) Method	255
	Composite Curve Method	257
	Linear Programming Method	258
9.3	Networks for Maximum Energy Recovery	261
	Stream Matching at the Pinch	261
	Mixed-Integer Linear Programming	264
9.4	Minimum Number of Heat Exchangers	267
	Reducing the Number of Heat Exchangers—Breaking Heat Loops	267
	Reducing the Number of Heat Exchangers—Stream Splitting	271
9.5	Threshold Approach Temperature	272
9.6	Optimum Approach Temperature	274
9.7	Superstructures for Minimization of Annual Costs	276
9.8	Multiple Utilities	278
	Designing HENs Assisted by the Grand Composite Curve	278
9.9	Heat-Integrated Distillation Trains	280
	Impact of Operating Pressure	281

- Multiple-Effect Distillation 282
- Heat Pumping, Vapor Recompression, and Reboiler Flashing 283
- 9.10 Heat Engines and Heat Pumps 284
  - Positioning Heat Engines and Heat Pumps 287
  - Optimal Design 288
- 9.11 Summary 290
  - Heat-Integration Software 290
  - References 291
  - Exercises 291

### **9S Supplement to Chapter 9—Second Law Analysis**

- 9S.0 Objectives
- 9S.1 Introduction
- 9S.2 The System and Surroundings
- 9S.3 Energy Transfer
- 9S.4 Thermodynamic Properties
  - Typical Entropy Changes
  - Thermodynamic Availability
  - Typical Availability Changes
- 9S.5 Equations for Second Law Analysis
- 9S.6 Examples of Lost Work Calculations
  - Nitrogen Compression
  - Propane Refrigeration
- 9S.7 Thermodynamic Efficiency
- 9S.8 Causes of Lost Work
- 9S.9 Three Examples of Lost Work Analysis
  - Refrigeration Cycle
  - Propylene-Propane Separation
  - Cyclohexane Process
- 9S.10 Summary
- 9S.11 References
- 9S.12 Exercises

## **Chapter 10**

### **Mass Exchanger Networks 297**

- 10.0 Objectives 297
- 10.1 Introduction 297
- 10.2 Minimum Mass-Separating Agent 299
  - Approach to Phase Equilibrium 299
  - Concentration-Interval (CI) Method 299
  - Composite Curve Method 302
- 10.3 Mass Exchange Networks for Minimum External MSA 303
  - Stream Matching at the Pinch 304
  - Stream Splitting at the Pinch 304
- 10.4 Minimum Number of Mass Exchangers 306
  - Reducing the Number of Mass Exchangers—Breaking Mass Loops 306
- 10.5 Advanced Topics 306



- 10.6 Summary 307
- References 307
- Exercises 307

## Chapter 11

### Batch Process Design 309

- 11.0 Objectives 309
- 11.1 Introduction 309
- 11.2 Design of Batch Process Units 310
  - Batch Processing 310
  - Fed-Batch Processing 311
  - Batch-Product Removal 313
- 11.3 Design of Reactor–Separator Processes 314
- 11.4 Design of Single-Product Processing Sequences 316
  - Batch Cycle Times 316
  - Intermediate Storage 318
  - Batch Size 318
- 11.5 Design of Multiproduct Processing Sequences 318
  - Scheduling and Designing Multiproduct Plants 319
- 11.6 Summary 320
- References 320
- Exercises 320

## Chapter 12

### Plantwide Control 322

- 12.0 Objectives 322
- 12.1 Introduction 322
- 12.2 Control System Configuration 325
  - Classification of Process Variables 325
  - Selection of Controlled (Output) Variables 326
  - Selection of Manipulated Variables 326
  - Selection of Measured Variables 327
  - Degrees-of-Freedom Analysis 327
- 12.3 Qualitative Plantwide Control System Synthesis 331
- 12.4 Summary 338
- References 338
- Exercises 339

### 12S Supplement to Chapter 12—Flowsheet Controllability Analysis

- 12S.0 Objectives
- 12S.1 Generation of Linear Models in Standard Forms
- 12S.2 Quantitative Measures for Controllability and Resiliency
  - Relative-Gain Array (RGA)
  - Properties of Steady-State RGA
  - Dynamic RGA (McAvoy, 1983)
  - The RGA as a Measure of Process Sensitivity to Uncertainty
  - Using the Disturbance Cost to Assess Resiliency to Disturbances
- 12S.3 Toward Automated Flowsheet C&R Diagnosis
  - Short-Cut C&R Diagnosis

	Generating Low-Order Dynamic Models
	Steady-State Gain Matrix, $\underline{\underline{K}}^c$
	Dynamics Matrix, $\underline{\underline{\psi}}^c\{s\}$
	Distillation Columns
	Heat Exchangers
12S.4	Control Loop Definition and Tuning
	Definition of PID Control Loop
	Controller Tuning
	Model-Based PI-Controller Tuning
12S.5	Case Studies
	Case Study 12S.1 Exothermic Reactor Design for the Production of Propylene Glycol
	Case Study 12S.2 Two Alternative Heat Exchanger Networks
	Case Study 12S.3 Interaction of Design and Control in the MCB Separation Process
12S.6	MATLAB for C&R Analysis
12S.7	Summary
12S.8	References
12S.9	Exercises

## Chapter 13

### Product Design Case Studies for Basic Chemicals 341

13.0	Objectives	341
13.1	Introduction	341
13.2	Ammonia Case Study	341
	Project Charter and New Technologies	341
	Innovation Map	342
	Concept Stage	344
	Feasibility Stage	345
	Development Stage	360
	Postscript	360
13.3	Environmentally Friendly Refrigerant Case Study	361
	Project Charter	361
	Molecular-Structure Design	361
	Innovation Map	362
	Concept Stage	362
	Feasibility Stage	362
	Development Stage	363
13.4	Water-Dispersible $\beta$ -Carotene Case Study	363
	Project Charter	363
	Innovation Map	364
	Concept Stage	366
	Coloration, Stability, and Bio-Availability	367
	Preferred Delivery Form	367
13.5	Summary	369
	References	369
	Exercises	370

**PART TWO PRODUCT DESIGN FOR INDUSTRIAL CHEMICALS 371**

<b>Chapter 14</b>	<b>New Technologies for Industrial Chemical Products 375</b>
14.0	Objectives 375
14.1	Introduction 375
14.2	Innovation Map for Thin-Glass Substrates in LCDs 377
	Thin-Glass Substrates 378
	Innovation Map 378
	Materials Technology Development 380
	Process/Manufacturing Technology: Corning Glass-Fusion Process 381
14.3	Innovation Map for Crayon Mixtures 383
	History of Crayons 383
	Innovation Map 383
	Materials Technology Development 386
	Process/Manufacturing Technology 386
	Technology Protection 386
	Environmental Concerns 387
14.4	Summary 387
	References 387      Exercises 388

**Chapter 15 Product Design Case Studies for Industrial Chemicals 389**

15.0	Objectives 389
15.1	Introduction 389
15.2	LCD Glass Substrate Case Study 389
	Project Charter 389
	Concept Stage 390
	Feasibility Stage 395
	Development Stage 398
	Manufacturing Stage 398
	Product-Introduction Stage 398
15.3	Washable Crayon Case Study 399
	Project Charter 399
	Concept Stage 400
15.4	Summary 405
	References 405      Exercises 405

**PART THREE PRODUCT DESIGN FOR CONFIGURED CONSUMER PRODUCTS 407****Chapter 16 New Technologies for Configured Consumer Products 411**

16.0	Objectives 411
16.1	Introduction 411
16.2	Innovation Map for the Incandescent Light Bulb 412

- Innovation and Product Design of the Incandescent Light Bulb 413
- Halogen Light Bulb Technology 414
- 16.3 Innovation Map for Home Hemodialysis Device 421
  - Hemodialysis Device Inventions 423
  - Innovation Map 424
- 16.4 Innovation Map for High-Throughput Screening of Kinase Inhibitors 430
  - Kinase Reactions and Lab-on-a-Chip Inventions 430
  - Innovation Map 433
- 16.5 Summary 439
  - References 439
  - Exercises 440

### **16S Supplement to Chapter 16**

- 16S.1 Halogen Light Bulb Model

## **Chapter 17**

### **Product Design Case Studies for Configured Consumer Products 442**

- 17.0 Objectives 442
- 17.1 Introduction 442
- 17.2 Halogen Light Bulb Case Study 442
  - Project Charter 442
  - Concept Stage 444
  - Feasibility Stage 451
  - Development Stage 453
  - Manufacturing Stage 453
  - Product-Introduction Stage 454
- 17.3 Home Hemodialysis Device Case Study 454
  - Project Charter 454
  - Concept Stage 454
  - Feasibility Stage 456
  - Development Stage 456
- 17.4 High-Throughput Screening of Kinase Inhibitors Case Study 456
  - Concept Stage 456
  - Feasibility Stage 461
  - Development Stage 464
- 17.5 Summary 464
  - References 465
  - Exercises 465

## **PART FOUR DETAILED DESIGN, EQUIPMENT SIZING, OPTIMIZATION, AND PRODUCT-QUALITY ANALYSIS 467**

## **Chapter 18**

### **Design of Heat Exchangers 469**

- 18.0 Objectives 469
- 18.1 Introduction 469
  - Heat Duty 469
  - Heat-Transfer Media 471
  - Temperature-Driving Force for Heat Transfer 472
  - Pressure Drop 475

18.2	Equipment for Heat Exchange	475
	Double-Pipe Heat Exchangers	475
	Shell-and-Tube Heat Exchangers	475
	Air-Cooled Heat Exchangers	481
	Compact Heat Exchangers	481
	Furnaces	482
	Temperature-Driving Forces in Shell-and-Tube Heat Exchangers	483
18.3	Heat-Transfer Coefficients and Pressure Drop	484
	Estimation of Overall Heat-Transfer Coefficients	487
	Estimation of Individual Heat-Transfer Coefficients and Frictional Pressure Drop	487
	Turbulent Flow in Straight, Smooth Ducts, Pipes, and Tubes of Circular Cross Section	487
	Turbulent Flow in the Annular Region Between Straight, Smooth Concentric Pipes of Circular Cross Section	490
	Turbulent Flow on the Shell Side of Shell-and-Tube Heat Exchangers	490
	Heat-Transfer Coefficients for Laminar-Flow, Condensation, Boiling, and Compact Heat Exchangers	491
18.4	Design of Shell-and-Tube Heat Exchangers	492
18.5	Summary	496
	References	496
	Exercises	496

## Chapter 19

### Design of Separation Towers 498

19.0	Objectives	498
19.1	Operating Conditions	498
19.2	Fenske–Underwood–Gilliland (FUG) Shortcut Method for Ordinary Distillation	499
19.3	Kremser Shortcut Method for Absorption and Stripping	500
19.4	Rigorous Multicomponent, Multi-Equilibrium-Stage Methods with a Simulator	502
19.5	Plate Efficiency and HETP	503
19.6	Tower Diameter	504
	Tray Towers	504
	Packed Towers	505
19.7	Pressure Drop and Weeping	506
19.8	Summary	508
	References	508
	Exercises	509

## Chapter 20

### Design of Pumps, Compressors, and Expanders 510

20.0	Objectives	510
20.1	Pumps	510
	Centrifugal Pumps	510
	Positive-Displacement Pumps	512
	Pump Models in Simulators	513
20.2	Compressors and Expanders	514
	Centrifugal Compressors	514

- Positive-Displacement Compressors 514
- Expanders 515
- Compressor and Expander Models in Simulators 516
- 20.3 Summary 517
- References 517 Exercises 517

## Chapter 21

### Polymer Extrusion 518

- 21.0 Objectives 518
- 21.1 Introduction 518
- 21.2 Compounding Technologies 518
- 21.3 Compounding Machinery 520
  - Single-Screw Extruder 520
  - Reciprocating Single-Screw Extruder 520
  - Twin-Screw Extruder 521
- 21.4 Understanding Polymeric Materials 522
- 21.5 Feeding Protocols 526
- 21.6 Screw Design 528
- 21.7 Setting the Processing Conditions 531
- 21.8 Summary 533
- References 533 Exercises 533

## Chapter 22

### Cost Accounting and Capital Costs 534

- 22.0 Objectives 534
- 22.1 Accounting 534
  - Debits and Credits 534
  - The Annual Report (Form 10-K) 535
  - The Balance Sheet 536
  - The Income Statement 538
  - The Cash Flow Statement 539
  - Financial Ratio Analysis 540
  - Cost Accounting 541
- 22.2 Cost Indexes and Capital Investment 542
  - Cost Indexes 542
  - Commodity Chemicals 543
  - Economy-of-Scale and the Six-Tenths Factor 544
  - Typical Plant Capacities and Capital Investments for Commodity Chemicals 545
- 22.3 Capital Investment Costs 546
  - Direct Materials and Labor (M&L) 548
  - Indirect Costs 549
  - Other Investment Costs 550
  - Example of an Estimate of Capital Investment 552
- 22.4 Estimation of the Total Capital Investment 553
  - Method 1. Order-of-Magnitude Estimate (Based on the Method of Hill, 1956) 553

	Method 2. Study Estimate (Based on the Overall Factor Method of Lang, 1947a, b, and 1948)	555
	Method 3. Preliminary Estimate (Based on the Individual Factors Method of Guthrie, 1969, 1974)	557
22.5	Purchase Costs of the Most Widely Used Process Equipment	558
	Pumps and Electric Motors	559
	Pump and Motor Purchase Costs	560
	Fans, Blowers, and Compressors	565
	Heat Exchangers	570
	Fired Heaters	573
	Pressure Vessels and Towers for Distillation, Absorption, and Stripping	573
22.6	Purchase Costs of Other Chemical Processing Equipment	580
	Adsorption Equipment	580
	Agitators (Propellers and Turbines)	580
	Autoclaves	580
	Crystallizers	581
	Drives Other than Electric Motors	581
	Dryers	581
	Dust Collectors	582
	Evaporators	582
	Fired Heaters for Specific Purposes	582
	Liquid–Liquid Extractors	583
	Membrane Separations	583
	Mixers for Powders, Pastes, and Doughs	583
	Power Recovery	584
	Screens	584
	Size Enlargement	584
	Size Reduction Equipment	584
	Solid–Liquid Separation Equipment (Thickeners, Clarifiers, Filters, Centrifuges, and Expression)	585
	Solids-Handling Systems	587
	Storage Tanks and Vessels	588
	Vacuum Systems	589
	Wastewater Treatment	596
22.7	Equipment Sizing and Capital Cost Estimation Using the Aspen Icarus Process Evaluator (IPE)	596
22.8	Summary	596
	References	596
	Exercises	597
<b>22S Supplement to Chapter 22</b>		
22S.1	Equipment Sizing and Capital Cost Estimation Using the Aspen Icarus Process Evaluator (IPE)	

## Chapter 23

<b>Manufacturing Costs and Profitability Analysis</b>		<b>602</b>
23.0	Objectives	602
23.1	Introduction	602

23.2	Annual Sales Revenues, Production Costs, and the Cost Sheet	603
	Sales Revenue	603
	Feedstocks	605
	Utilities	605
	Labor-Related Operations, O	610
	Maintenance, M	611
	Operating Overhead	612
	Property Taxes and Insurance	612
	Depreciation, D	612
	Rental Fees	612
	Licensing Fees	613
	Cost of Manufacture, COM	613
	Total Production Cost, C	613
	Pre-Tax (Gross) Earnings and After-Tax (Net) Earnings (Profit)	614
23.3	Working Capital and Total Capital Investment	615
23.4	Approximate Profitability Measures	615
	Return on Investment (ROI)	616
	Payback Period (PBP)	616
	Venture Profit (VP)	617
	Annualized Cost ( $C_A$ )	617
	Product Selling Price for Profitability	618
23.5	Time Value of Money	619
	Compound Interest	620
	Nominal and Effective Interest Rates	621
	Continuous Compounding of Interest	621
	Annuities	622
	Present Worth of an Annuity	624
	Comparing Alternative Equipment Purchases	625
23.6	Cash Flow and Depreciation	627
	Depreciation	628
	Depletion	632
23.7	Rigorous Profitability Measures	633
	Net Present Value (NPV)	633
	Investor's Rate of Return (IRR or DCFRR)	633
	Inflation	635
23.8	Profitability Analysis Spreadsheet	636
23.9	Summary	636
	References	637
	Exercises	637

### **23S Supplement to Chapter 23**

23S.1	Profitability Analysis Spreadsheet
-------	------------------------------------

## **Chapter 24**

### **Optimization for Design 642**

24.0	Objectives	642
24.1	Introduction	642



- 24.2 General Formulation of the Optimization Problem 643
  - Objective Function and Decision Variables 643
  - Equality Constraints 644
  - Inequality Constraints 644
  - Lower and Upper Bounds 644
- 24.3 Classification of Optimization Problems 644
- 24.4 Linear Programming (LP) 647
- 24.5 Nonlinear Programming (NLP) with a Single Variable 649
  - Golden-Section Search 649
- 24.6 Conditions for Nonlinear Programming (NLP) by Gradient Methods with Two or More Decision Variables 652
  - General Formulation 652
  - Stationarity Conditions 652
  - Solution of the Stationarity Equations 652
- 24.7 Optimization Algorithm 653
  - Repeated Simulation 655
  - Infeasible Path Approach 655
  - Compromise Approach 655
  - Practical Aspects of Flowsheet Optimization 655
- 24.8 Flowsheet Optimizations—Case Studies 656
- 24.9 Summary 658
  - References 658
  - Exercises 659

## Chapter 25

### Design for Six-Sigma 662

- 25.0 Objectives 662
- 25.1 Introduction 662
- 25.2 Six-Sigma Methodology in Product Design and Manufacturing 662
  - Definitions 662
  - Cost of Defects 664
  - Methods to Monitor and Reduce Variance 665
  - Six-Sigma for Product Design 666
- 25.3 Example Applications 667
- 25.4 Summary 677
  - References 677
  - Exercises 678

### 25S Supplement to Chapter 25

- 25S.1 Penicillin Fermenter Model

## PART FIVE DESIGN REPORT 679

### Chapter 26

#### Written and Oral Reports 681

- 26.0 Objectives 681
- 26.1 Contents of the Written Report 682
  - Sections of the Report 682
  - Preparation of the Written Report 687

	Sample Design Reports	689
26.2	Oral Design Presentation	689
	Typical Presentation	689
	Media for the Presentation	689
	Rehearsing the Presentation	690
	Written Handout	690
	Evaluation of the Oral Presentation	690
	Videotapes and DVDs	690
26.3	Award Competition	691
26.4	Summary	692
	References	692

## **APPENDIXES**

<b>I.</b>	<b>Heterogeneous Residue Curves</b>	<b>693</b>
<b>II.</b>	<b>Design Problems</b>	<b>694</b>
	A-II.0 Contents and Introduction	694
<b>III.</b>	<b>Materials of Construction</b>	<b>697</b>
<b>IIS.</b>	<b>Supplement to Appendix II</b>	

## **INDICES**

	<b>Table of Acronyms</b>	<b>699</b>
	<b>Author Index</b>	<b>706</b>
	<b>Subject Index</b>	<b>711</b>