

# ANALYSIS, SYNTHESIS, AND DESIGN OF CHEMICAL PROCESSES

FIFTH EDITION

RICHARD TURTON | JOSEPH A. SHAEIWITZ  
DEBANGSU BHATTACHARYYA | WALLACE B. WHITING



PRENTICE HALL INTERNATIONAL SERIES IN THE  
PHYSICAL AND CHEMICAL ENGINEERING SCIENCES



**Analysis, Synthesis,  
and Design  
of Chemical Processes**

*Fifth Edition*

# Analysis, Synthesis and Design of Chemical Processes

## Table of Contents

Cover

Half Title

Title Page

Copyright Page

Contents

Preface

About the Authors

List of Nomenclature

Chapter 0 Outcomes Assessment

0.1 Student Self-Assessment

0.2 Assessment by Faculty

0.3 Summary

References

## SECTION I: Conceptualization and Analysis of Chemical Processes

Chapter 1 Diagrams for Understanding Chemical Processes

1.1 Block Flow Diagram (BFD)

1.1.1 Block Flow Process Diagram

1.1.2 Block Flow Plant Diagram

1.2 Process Flow Diagram (PFD)

1.2.1 Process Topology

1.2.2 Stream Information

1.2.3 Equipment Information

1.2.4 Combining Topology, Stream Data, and Control Strategy to Give a PFD

1.3 Piping and Instrumentation Diagram (P&ID)

1.4 Additional Diagrams

1.5 Three-Dimensional Representation of a Process

# **Table of Contents**

## 1.6 The 3-D Plant Model

## 1.7 Operator and 3-D Immersive Training Simulators

### 1.7.1 Operator Training Simulators (OTS)

### 1.7.2 3-D Immersive Training Simulators (ITS)

### 1.7.3 Linking the ITS with an OTS

## 1.8 Summary

## References

## Short Answer Questions

## Problems

# Chapter 2 The Structure and Synthesis of Process Flow Diagrams

## 2.1 Hierarchy of Process Design

## 2.2 Step 1 Batch versus Continuous Process

## 2.3 Step 2 The Input/Output Structure of the Process

### 2.3.1 Process Concept Diagram

### 2.3.2 The Input/Output Structure of the Process Flow Diagram

### 2.3.3 The Input/Output Structure and Other Features of the Generic Block Flow Process Diagram

### 2.3.4 Other Considerations for the Input/Output Structure of the Process Flowsheet

### 2.3.5 What Information Can Be Determined Using the Input/Output Diagram for a Process?

## 2.4 Step 3 The Recycle Structure of the Process

### 2.4.1 Efficiency of Raw Material Usage

### 2.4.2 Identification and Definition of the Recycle Structure of the Process

### 2.4.3 Other Issues Affecting the Recycle Structure That Lead to Process Alternatives

## 2.5 Step 4 General Structure of the Separation System

## 2.6 Step 5 Heat-Exchanger Network or Process Energy Recovery System

## 2.7 Information Required and Sources

## 2.8 Summary

## References

## Short Answer Questions

## Problems

# Chapter 3 Batch Processing

## 3.1 Design Calculations for Batch Processes

## 3.2 Gantt Charts and Scheduling

## 3.3 Nonoverlapping Operations, Overlapping Operations, and Cycle Times

## 3.4 Flowshop and Jobshop Plants

# **Table of Contents**

3.4.1 Flowshop Plants

3.4.2 Jobshop Plants

## **3.5 Product and Intermediate Storage and Parallel Process Units**

3.5.1 Product Storage for Single-Product Campaigns

3.5.2 Intermediate Storage

3.5.3 Parallel Process Units

## **3.6 Design of Equipment for Multiproduct Batch Processes**

## **3.7 Summary**

References

Short Answer Questions

Problems

## **Chapter 4 Chemical Product Design**

4.1 Strategies for Chemical Product Design

4.2 Needs

4.3 Ideas

4.4 Selection

4.5 Manufacture

4.6 Batch Processing

4.7 Economic Considerations

4.8 Summary

References

## **Chapter 5 Tracing Chemicals through the Process Flow Diagram**

5.1 Guidelines and Tactics for Tracing Chemicals

5.2 Tracing Primary Paths Taken by Chemicals in a Chemical Process

5.3 Recycle and Bypass Streams

5.4 Tracing Nonreacting Chemicals

5.5 Limitations

5.6 Written Process Description

5.7 Summary

Problems

## **Chapter 6 Understanding Process Conditions**

6.1 Conditions of Special Concern for the Operation of Separation and Reactor Systems

6.1.1 Pressure

# Table of Contents

- 6.1.2 Temperature
- 6.2 Reasons for Operating at Conditions of Special Concern
- 6.3 Conditions of Special Concern for the Operation of Other Equipment
- 6.4 Analysis of Important Process Conditions
  - 6.4.1 Evaluation of Reactor R-101
  - 6.4.2 Evaluation of High-Pressure Phase Separator V-102
  - 6.4.3 Evaluation of Large Temperature Driving Force in Exchanger E-101
  - 6.4.4 Evaluation of Exchanger E-102
  - 6.4.5 Pressure Control Valve on Stream 8
  - 6.4.6 Pressure Control Valve on Stream from V-102 to V-103
- 6.5 Summary
- References
- Short Answer Questions
- Problems

## SECTION II: Engineering Economic Analysis of Chemical Processes

### Chapter 7 Estimation of Capital Costs

- 7.1 Classifications of Capital Cost Estimates
- 7.2 Estimation of Purchased Equipment Costs
  - 7.2.1 Effect of Capacity on Purchased Equipment Cost
  - 7.2.2 Effect of Time on Purchased Equipment Cost
- 7.3 Estimating the Total Capital Cost of a Plant
  - 7.3.1 Lang Factor Technique
  - 7.3.2 Module Costing Technique
  - 7.3.3 Bare Module Cost for Equipment at Base Conditions
  - 7.3.4 Bare Module Cost for Non-Base-Case Conditions
  - 7.3.5 Combination of Pressure and MOC Information to Give the Bare Module Factor,  $F$ , and Bare Module Cost,  $C$
  - 7.3.6 Algorithm for Calculating Bare Module Costs
  - 7.3.7 Grassroots (Green Field) and Total Module Costs
  - 7.3.8 A Computer Program (CAPCOST) for Capital Cost Estimation Using the Equipment Module Approach
- 7.4 Estimation of Plant Costs Based on Capacity Information
- 7.5 Summary
- References
- Short Answer Questions

# **Table of Contents**

Problems

## **Chapter 8 Estimation of Manufacturing Costs**

8.1 Factors Affecting the Cost of Manufacturing a Chemical Product

8.2 Cost of Operating Labor

8.3 Utility Costs

8.3.1 Background Information on Utilities

8.3.2 Calculation of Utility Costs

8.4 Raw Material Costs

8.5 Yearly Costs and Stream Factors

8.6 Estimating Utility Costs from the PFD

8.7 Cost of Treating Liquid and Solid Waste Streams

8.8 Evaluation of Cost of Manufacture for the Production of Benzene via the Hydrodealkylation of Toluene

8.9 Summary

References

Short Answer Questions

Problems

## **Chapter 9 Engineering Economic Analysis**

9.1 Investments and the Time Value of Money

9.2 Different Types of Interest

9.2.1 Simple Interest

9.2.2 Compound Interest

9.2.3 Interest Rates Changing with Time

9.3 Time Basis for Compound Interest Calculations

9.3.1 Effective Annual Interest Rate

9.3.2 Continuously Compounded Interest

9.4 Cash Flow Diagrams

9.4.1 Discrete Cash Flow Diagram

9.4.2 Cumulative Cash Flow Diagram

9.5 Calculations from Cash Flow Diagrams

9.5.1 Annuities A Uniform Series of Cash Transactions

9.5.2 Discount Factors

9.6 Inflation

9.7 Depreciation of Capital Investment



# **Table of Contents**

9.7.1 Fixed Capital, Working Capital, and Land

9.7.2 Different Types of Depreciation

9.7.3 Current Depreciation Method (2017): Modified Accelerated Cost Recovery System (MACRS)

9.8 Taxation, Cash Flow, and Profit

9.9 Summary

References

Short Answer Questions

Problems

## **Chapter 10 Profitability Analysis**

10.1 A Typical Cash Flow Diagram for a New Project

10.2 Profitability Criteria for Project Evaluation

10.2.1 Nondiscounted Profitability Criteria

10.2.2 Discounted Profitability Criteria

10.3 Comparing Several Large Projects: Incremental Economic Analysis

10.4 Establishing Acceptable Returns from Investments: The Concept of Risk

10.5 Evaluation of Equipment Alternatives

10.5.1 Equipment with the Same Expected Operating Lives

10.5.2 Equipment with Different Expected Operating Lives

10.6 Incremental Analysis for Retrofitting Facilities

10.6.1 Nondiscounted Methods for Incremental Analysis

10.6.2 Discounted Methods for Incremental Analysis

10.7 Evaluation of Risk in Evaluating Profitability

10.7.1 Forecasting Uncertainty in Chemical Processes

10.7.2 Quantifying Risk

10.8 Profit Margin Analysis

10.9 Summary

References

Short Answer Questions

Problems

## **SECTION III: Synthesis and Optimization of Chemical Processes**

### **Chapter 11 Utilizing Experience-Based Principles to Confirm the Suitability of a Process Design**

11.1 The Role of Experience in the Design Process

11.1.1 Introduction to Technical Heuristics and Shortcut Methods



# **Table of Contents**

11.1.2 Maximizing the Benefits Obtained from Experience

11.2 Presentation of Tables of Technical Heuristics and Guidelines

11.3 Summary

List of Informational Tables

References

Problems

## **Chapter 12 Synthesis of the PFD from the Generic BFD**

12.1 Information Needs and Sources

12.1.1 Interactions with Other Engineers and Scientists

12.1.2 Reaction Kinetics Data

12.1.3 Physical Property Data

12.2 Reactor Section

12.3 Separator Section

12.3.1 General Guidelines for Choosing Separation Operations

12.3.2 Sequencing of Distillation Columns for Simple Distillation

12.3.3 Azeotropic Distillation

12.4 Reactor Feed Preparation and Separator Feed Preparation Sections

12.5 Recycle Section

12.6 Environmental Control Section

12.7 Major Process Control Loops

12.8 Flow Summary Table

12.9 Major Equipment Summary Table

12.10 Summary

References

General Reference

Problems

## **Chapter 13 Synthesis of a Process Using a Simulator and Simulator Troubleshooting**

13.1 The Structure of a Process Simulator

13.2 Information Required to Complete a Process Simulation: Input Data

13.2.1 Selection of Chemical Components

13.2.2 Selection of Physical Property Models

13.2.3 Selection and Input of Flowsheet Topology

13.2.4 Selection of Feed Stream Properties

# **Table of Contents**

13.2.5 Selection of Equipment Parameters

13.2.6 Selection of Output Display Options

13.2.7 Selection of Convergence Criteria and Running a Simulation

13.2.8 Common Errors in Using Simulators

## **13.3 Handling Recycle Streams**

## **13.4 Choosing Thermodynamic Models**

13.4.1 Pure-Component Properties

13.4.2 Enthalpy

13.4.3 Phase Equilibria

13.4.4 Using Thermodynamic Models

## **13.5 Case Study: Toluene Hydrodealkylation Process**

## **13.6 Electrolyte Systems Modeling**

13.6.1 Fundamentals of Modeling Electrolyte Systems

13.6.2 Steps Needed to Build the Model of an Aqueous Electrolyte System and the Estimation of Parameters

## **13.7 Solids Modeling**

13.7.1 Physical Properties

13.7.2 Parameter Requirements for Solids Model

## **Appendix 13.1**

Calculation of Excess Gibbs Energy for Electrolyte Systems

## **Appendix 13.2**

Steps to Build a Model of a Distillation Column for an Electrolyte System Using a Rate-Based Simulation with a Film Model for Mass Transfer, the Parameters Required at Each Stage, and Possible Sources of These Parameters

## **13.8 Summary**

References

Short Answer Questions

Problems

## **Chapter 14 Process Optimization**

### **14.1 Background Information on Optimization**

14.1.1 Common Misconceptions

14.1.2 Estimating Problem Difficulty

14.1.3 Top-Down and Bottom-Up Strategies

14.1.4 Communication of Optimization Results

### **14.2 Strategies**

# **Table of Contents**

- 14.2.1 Base Case
- 14.2.2 Objective Functions
- 14.2.3 Analysis of the Base Costs
- 14.2.4 Identifying and Prioritizing Key Decision Variables

## **14.3 Topological Optimization**

- 14.3.1 Introduction
- 14.3.2 Elimination of Unwanted Nonhazardous By-Products or Hazardous Waste Streams
- 14.3.3 Elimination and Rearrangement of Equipment
- 14.3.4 Alternative Separation Schemes and Reactor Configurations

## **14.4 Parametric Optimization**

- 14.4.1 Single-Variable Optimization: A Case Study on T-201, the DME Separation Column
- 14.4.2 Two-Variable Optimization: The Effect of Pressure and Reflux Ratio on T-201, the DME Separation Column
- 14.4.3 Flowsheet Optimization Using Key Decision Variables

## **14.5 Lattice Search, Response Surface, and Mathematical Optimization Techniques**

## **14.6 Process Flexibility and the Sensitivity of the Optimum**

## **14.7 Optimization in Batch Systems**

- 14.7.1 Problem of Scheduling Equipment
- 14.7.2 Problem of Optimum Cycle Time

## **14.8 Summary**

## **References**

## **Short Answer Questions**

## **Problems**

# **Chapter 15 Pinch Technology**

- 15.1 Introduction
- 15.2 Heat Integration and Network Design
- 15.3 Composite Temperature-Enthalpy Diagram
- 15.4 Composite Enthalpy Curves for Systems without a Pinch
- 15.5 Using the Composite Enthalpy Curve to Estimate Heat-Exchanger Surface Area
- 15.6 Effectiveness Factor (F) and the Number of Shells
- 15.7 Combining Costs to Give the EAOC for the Network
- 15.8 Other Considerations
  - 15.8.1 Materials of Construction and Operating Pressure Issues
  - 15.8.2 Problems with Multiple Utilities
  - 15.8.3 Handling Streams with Phase Changes

# **Table of Contents**

15.9 Heat-Exchanger Network Synthesis Analysis and Design (HENSAD) Program

15.10 Mass-Exchange Networks

15.11 Summary

References

Short Answer Questions

Problems

## **Chapter 16 Advanced Topics Using Steady-State Simulators**

16.1 Why the Need for Advanced Topics in Steady-State Simulation?

16.2 User-Added Models

16.2.1 Unit Operation Models

16.2.2 User Thermodynamic and Transport Models

16.2.3 User Kinetic Models

16.3 Solution Strategy for Steady-State Simulations

16.3.1 Sequential Modular (SM)

16.3.2 Equation-Oriented (EO)

16.3.3 Simultaneous Modular (SMod)

16.4 Studies with the Steady-State Simulation

16.4.1 Sensitivity Studies

16.4.2 Optimization Studies

16.5 Estimation of Physical Property Parameters

16.6 Summary

References

Short Answer Questions

Problems

## **Chapter 17 Using Dynamic Simulators in Process Design**

17.1 Why Is There a Need for Dynamic Simulation?

17.2 Setting Up a Dynamic Simulation

17.2.1 Step 1: Topological Change in the Steady-State Simulation

17.2.2 Step 2: Equipment Geometry and Size

17.2.3 Step 3: Additional Dynamic Data/Dynamic Specification

17.3 Dynamic Simulation Solution Methods

17.3.1 Initialization

17.3.2 Solution of the DAE System

17.4 Process Control

# Table of Contents

17.5 Summary

References

Short Answer Questions

Problems

## Chapter 18 Regulation and Control of Chemical Processes with Applications Using Commercial Software

18.1 A Simple Regulation Problem

18.2 The Characteristics of Regulating Valves

18.3 Regulating Flowrates and Pressures

18.4 The Measurement of Process Variables

18.5 Common Control Strategies Used in Chemical Processes

18.5.1 Feedback Control and Regulation

18.5.2 Feed-Forward Control and Regulation

18.5.3 Combination Feedback and Feed-Forward Control

18.5.4 Cascade Regulation

18.5.5 Ratio Control

18.5.6 Split-Range Control

18.6 Exchanging Heat and Work between Process and Utility Streams

18.6.1 Increasing the Pressure of a Process Stream and Regulating Its Flowrate

18.6.2 Exchanging Heat between Process Streams and Utilities

18.6.3 Exchanging Heat between Process Streams

18.7 Logic Control

18.8 Advanced Process Control

18.8.1 Statistical Process Control (SPC)

18.8.2 Model-Based Control

18.9 Case Studies

18.9.1 The Cumene Reactor, R-801

18.9.2 A Basic Control System for a Binary Distillation Column

18.9.3 A More Sophisticated Control System for a Binary Distillation Column

18.10 Putting It All Together: The Operator Training Simulator (OTS)

18.11 Summary

References

Problems

## SECTION IV: Chemical Equipment Design and Performance Process

# **Table of Contents**

## **Equipment Design and Performance**

### **Chapter 19 Process Fluid Mechanics**

#### **19.1 Basic Relationships in Fluid Mechanics**

19.1.1 Mass Balance

19.1.2 Mechanical Energy Balance

19.1.3 Force Balance

#### **19.2 Fluid Flow Equipment**

19.2.1 Pipes

19.2.2 Valves

19.2.3 Pumps

19.2.4 Compressors

#### **19.3 Frictional Pipe Flow**

19.3.1 Calculating Frictional Losses

19.3.2 Incompressible Flow

19.3.3 Compressible Flow

19.3.4 Choked Flow

#### **19.4 Other Flow Situations**

19.4.1 Flow Past Submerged Objects

19.4.2 Fluidized Beds

19.4.3 Flowrate Measurement

#### **19.5 Performance of Fluid Flow Equipment**

19.5.1 Base-Case Ratios

19.5.2 Net Positive Suction Head

19.5.3 Pump and System Curves

19.5.4 Compressors

19.5.5 Performance of the Feed Section to a Process

#### **References**

#### **Short Answer Questions**

#### **Problems**

### **Chapter 20 Process Heat Transfer**

#### **20.1 Basic Heat-Exchanger Relationships**

20.1.1 Countercurrent Flow

20.1.2 Cocurrent Flow

20.1.3 Streams with Phase Changes

20.1.4 Nonlinear Q versus T Curves

20.1.5 Overall Heat Transfer Coefficient, U, Varies along the Exchanger

# **Table of Contents**

## 20.2 Heat-Exchange Equipment Design and Characteristics

### 20.2.1 Shell-and-Tube Heat Exchangers

## 20.3 LMTD Correction Factor for Multiple Shell and Tube Passes

### 20.3.1 Background

### 20.3.2 Basic Configuration of a Single-Shell-Pass, Double-Tube-Pass (12) Exchanger

### 20.3.3 Multiple Shell-and-Tube-Pass Exchangers

### 20.3.4 Cross-Flow Exchangers

### 20.3.5 LMTD Correction and Phase Change

## 20.4 Overall Heat Transfer Coefficients Resistances in Series

## 20.5 Estimation of Individual Heat Transfer Coefficients and Fouling Resistances

### 20.5.1 Heat Transfer Resistances Due to Fouling

### 20.5.2 Thermal Conductivities of Common Metals and Tube Properties

### 20.5.3 Correlations for Film Heat Transfer Coefficients

## 20.6 Extended Surfaces

### 20.6.1 Rectangular Fin with Constant Thickness

### 20.6.2 Fin Efficiency for Other Fin Geometries

### 20.6.3 Total Heat Transfer Surface Effectiveness

## 20.7 Algorithm and Worked Examples for the Design of Heat Exchangers

### 20.7.1 Pressure Drop Considerations

### 20.7.2 Design Algorithm

## 20.8 Performance Problems

### 20.8.1 What Variables to Specify in Performance Problems

### 20.8.2 Using Ratios to Determine Heat-Exchanger Performance

### 20.8.3 Worked Examples for Performance Problems

## References

## Appendix 20.A: Heat-Exchanger Effectiveness Charts

## Appendix 20.B: Derivation of Fin Effectiveness for a Rectangular Fin

## Short Answer Questions

## Problems

# Chapter 21 Separation Equipment

## 21.1 Basic Relationships in Separations

### 21.1.1 Mass Balances

### 21.1.2 Energy Balances

### 21.1.3 Equilibrium Relationships

### 21.1.4 Mass Transfer Relationships

### 21.1.5 Rate Expressions



# Table of Contents

## 21.2 Illustrative Diagrams

21.2.1 TP-xy Diagrams

21.2.2 McCabe-Thiele Diagram

21.2.3 Dilute SolutionsThe Kremser and Colburn Methods

## 21.3 Equipment

21.3.1 Drums

21.3.2 Tray Towers

21.3.3 Packed Towers

21.3.4 Tray Tower or Packed Tower?

21.3.5 Performance of Packed and Tray Towers

Case Study

## 21.4 Extraction Equipment

21.4.1 Mixer-Settlers

21.4.2 Static and Pulsed Columns

21.4.3 Agitated Columns

21.4.4 Centrifugal Extractors

## 21.5 Gas Permeation Membrane Separations

21.5.1 Equipment

21.5.2 Models for Gas Permeation Membranes

21.5.3 Practical Issues

## References

## Short Answer Questions

## Problems

## Chapter 22 Reactors

### 22.1 Basic Relationships

22.1.1 Kinetics

22.1.2 Equilibrium

22.1.3 Additional Mass Transfer Effects

22.1.4 Mass Balances

22.1.5 Energy Balances

22.1.6 Reactor Models

### 22.2 Equipment Design for Nonisothermal Conditions

22.2.1 Nonisothermal Continuous Stirred Tank Reactor

22.2.2 Nonisothermal Plug Flow Reactor

22.2.3 Fluidized Bed Reactor

### 22.3 Performance Problems

# Table of Contents

- 22.3.1 Ratios for Simple Cases
- 22.3.2 More Complex Examples

References

Short Answer Questions

Problems

## Chapter 23 Other Equipment

### 23.1 Pressure Vessels

- 23.1.1 Material Properties
- 23.1.2 Basic Design Equations

### 23.2 Knockout Drums or Simple Phase Separators

- 23.2.1 Vapor-Liquid (V-L) Separation
- 23.2.2 Design of Vertical V-L Separators
- 23.2.3 Design of Horizontal V-L Separators
- 23.2.4 Mist Eliminators and Other Internals
- 23.2.5 Liquid-Liquid (L-L) Separation

### 23.3 Steam Ejectors

- 23.3.1 Estimating Air Leaks into Vacuum Systems and the Load for Steam Ejectors
- 23.3.2 Single-Stage Steam Ejectors
- 23.3.3 Multistage Steam Ejectors
- 23.3.4 Performance of Steam Ejectors

References

Short Answer Questions

Problems

## Chapter 24 Process Troubleshooting and Debottlenecking

### 24.1 Recommended Methodology

- 24.1.1 Elements of Problem-Solving Strategies
- 24.1.2 Application to Troubleshooting Problems

### 24.2 Troubleshooting Individual Units

- 24.2.1 Troubleshooting a Packed-Bed Absorber
- 24.2.2 Troubleshooting the Cumene Process Feed Section

### 24.3 Troubleshooting Multiple Units

- 24.3.1 Troubleshooting Off-Specification Acrylic Acid Product
- 24.3.2 Troubleshooting Steam Release in Cumene Reactor

### 24.4 A Process Troubleshooting Problem

### 24.5 Debottlenecking Problems

# Table of Contents

24.6 Summary

References

Problems

## SECTION V: The Impact of Chemical Engineering Design on Society

### Chapter 25 Ethics and Professionalism

#### 25.1 Ethics

25.1.1 Moral Autonomy

25.1.2 Rehearsal

25.1.3 Reflection in Action

25.1.4 Mobile Truth

25.1.5 Nonprofessional Responsibilities

25.1.6 Duties and Obligations

25.1.7 Codes of Ethics

25.1.8 Whistle-Blowing [12]

25.1.9 Ethical Dilemmas

25.1.10 Additional Ethics Heuristics

25.1.11 Other Resources

#### 25.2 Professional Registration

25.2.1 Engineer-in-Training

25.2.2 Registered Professional Engineer

#### 25.3 Legal Liability [13]

#### 25.4 Business Codes of Conduct [14, 15]

#### 25.5 Summary

References

Problems

### Chapter 26 Health, Safety, and the Environment

#### 26.1 Risk Assessment

26.1.1 Accident Statistics

26.1.2 Worst-Case Scenarios

26.1.3 The Role of the Chemical Engineer

#### 26.2 Regulations and Agencies

26.2.1 OSHA and NIOSH

26.2.2 Environmental Protection Agency (EPA)

26.2.3 Nongovernmental Organizations

#### 26.3 Fires and Explosions

# **Table of Contents**

26.3.1 Terminology

26.3.2 Pressure-Relief Systems

## **26.4 Process Hazard Analysis**

26.4.1 HAZOP (Hazard and Operability Study)

26.4.2 Dow Fire & Explosion Index and Chemical Exposure Index

## **26.5 Chemical Safety and Hazard Investigation Board**

## **26.6 Inherently Safe Design**

## **26.7 Summary**

## **26.8 Glossary**

References

Problems

## **Chapter 27 Green Engineering**

### **27.1 Environmental Regulations**

### **27.2 Environmental Fate of Chemicals**

### **27.3 Green Chemistry**

### **27.4 Pollution Prevention during Process Design**

### **27.5 Analysis of a PFD for Pollution Performance and Environmental Performance**

### **27.6 An Example of the Economics of Pollution Prevention**

### **27.7 Life Cycle Analysis**

### **27.8 Summary**

References

Problems

## **SECTION VI: Interpersonal and Communication Skills**

### **Chapter 28 Teamwork**

#### **28.1 Groups**

28.1.1 Characteristics of Effective Groups

28.1.2 Assessing and Improving the Effectiveness of a Group

28.1.3 Organizational Behaviors and Strategies

#### **28.2 Group Evolution**

28.2.1 Forming

28.2.2 Storming

28.2.3 Norming

28.2.4 Performing

#### **28.3 Teams and Teamwork**

# **Table of Contents**

28.3.1 When Groups Become Teams

28.3.2 Unique Characteristics of Teams

## **28.4 Misconceptions**

28.4.1 Team Exams

28.4.2 Overreliance on Team Members

## **28.5 Learning in Teams**

## **28.6 Other Reading**

## **28.7 Summary**

References

Problems

## **Chapter 29 Written and Oral Communication**

### **29.1 Audience Analysis**

### **29.2 Written Communication**

29.2.1 Design Reports

29.2.2 Transmittal Letters or Memos

29.2.3 Executive Summaries and Abstracts

29.2.4 Other Types of Written Communication

29.2.5 Exhibits (Figures and Tables)

29.2.6 References

29.2.7 Strategies for Writing

29.2.8 WVU and Auburn University Guidelines for Written Design Reports

### **29.3 Oral Communication**

29.3.1 Formal Oral Presentations

29.3.2 Briefings

29.3.3 Visual Aids

29.3.4 WVU and Auburn University Oral Presentation Guidelines

### **29.4 Software and Author Responsibility**

29.4.1 Spell Checkers

29.4.2 Thesaurus

29.4.3 Grammar Checkers

29.4.4 Graphs

29.4.5 Tables

29.4.6 Colors and Exotic Features

29.4.7 Raw Output from Process Simulators

### **29.5 Summary**

References

# **Table of Contents**

Problems

## **Chapter 30 A Report-Writing Case Study**

30.1 The Assignment Memorandum

30.2 Response Memorandum

30.3 Visual Aids

30.4 Example Reports

30.4.1 An Example of a Portion of a Student Written Report

30.4.2 An Example of an Improved Student Written Report

30.5 Checklist of Common Mistakes and Errors

30.5.1 Common Mistakes for Visual Aids

30.5.2 Common Mistakes for Written Text

## **Appendix A: Cost Equations and Curves for the CAPCOST Program**

### **A.1 Purchased Equipment Costs**

### **A.2 Pressure Factors**

A.2.1 Pressure Factors for Process Vessels

A.2.2 Pressure Factors for Other Process Equipment

### **A.3 Material Factors and Bare Module Factors**

A.3.1 Bare Module and Material Factors for Heat Exchangers, Process Vessels, and Pumps

A.3.2 Bare Module and Material Factors for the Remaining Process Equipment

### **References**

## **Appendix B: Information for the Preliminary Design of Fifteen Chemical Processes**

### **B.1 Dimethyl Ether (DME) Production, Unit 200**

B.1.1 Process Description

B.1.2 Reaction Kinetics

B.1.3 Simulation (CHEMCAD) Hints

B.1.4 References

### **B.2 Ethylbenzene Production, Unit 300**

B.2.1 Process Description [1, 2]

B.2.2 Reaction Kinetics

B.2.3 Simulation (CHEMCAD) Hints

# **Table of Contents**

B.2.4 References

## **B.3 Styrene Production, Unit 400**

B.3.1 Process Description [1, 2]

B.3.2 Reaction Kinetics

B.3.3 Simulation (CHEMCAD) Hints

B.3.4 References

## **B.4 Drying Oil Production, Unit 500**

B.4.1 Process Description

B.4.2 Reaction Kinetics

B.4.3 Simulation (CHEMCAD) Hints

B.4.4 Reference

## **B.5 Production of Maleic Anhydride from Benzene, Unit 600**

B.5.1 Process Description

B.5.2 Reaction Kinetics

B.5.3 Simulation (CHEMCAD) Hints

B.5.4 References

## **B.6 Ethylene Oxide Production, Unit 700**

B.6.1 Process Description [1, 2]

B.6.2 Reaction Kinetics

B.6.3 Simulation (CHEMCAD) Hints

B.6.4 References

## **B.7 Formalin Production, Unit 800**

B.7.1 Process Description [1, 2]

B.7.2 Reaction Kinetics

B.7.3 Simulation (CHEMCAD) Hints

B.7.4 References

## **B.8 Batch Production of L-Phenylalanine and L-Aspartic Acid, Unit 900**

B.8.1 Process Description

B.8.2 Reaction Kinetics

B.8.3 References

## **B.9 Acrylic Acid Production via The Catalytic Partial Oxidation of Propylene [15], Unit 1000**



# **Table of Contents**

B.9.1 Process Description

B.9.2 Reaction Kinetics and Reactor Configuration

B.9.3 Simulation (CHEMCAD) Hints

B.9.4 References

## **B.10 Production of Acetone via the Dehydrogenation of Isopropyl Alcohol (IPA) [14], Unit 1100**

B.10.1 Process Description

B.10.2 Reaction Kinetics

B.10.3 Simulation (CHEMCAD) Hints

B.10.4 References

## **B.11 Production of Heptenes from Propylene and Butenes [1], Unit 1200**

B.11.1 Process Description

B.11.2 Reaction Kinetics

B.11.3 Simulation (CHEMCAD) Hints

B.11.4 Reference

## **B.12 Design of a Shift Reactor Unit to Convert CO to CO<sub>2</sub>, Unit 1300**

B.12.1 Process Description

B.12.2 Reaction Kinetics

B.12.3 Simulation (Aspen Plus) Hints

B.12.4 Reference

## **B.13 Design of a Dual-Stage Selexol Unit to Remove CO<sub>2</sub> and H<sub>2</sub>S From Coal-Derived Synthesis Gas, Unit 1400**

B.13.1 Process Description

B.13.2 Simulation (Aspen Plus) Hints

B.13.3 References

## **B.14 Design of a Claus Unit for the Conversion of H<sub>2</sub>S to Elemental Sulfur, Unit 1500**

B.14.1 Process Description

B.14.2 Reaction Kinetics

B.14.3 Simulation (Aspen Plus) Hints

B.14.4 References

## **B.15 Modeling a Downward-Flow, Oxygen-Blown, Entrained-Flow Gasifier,**

# **Table of Contents**

## Unit 1600

B.15.1 Process Description

B.15.2 Reaction Kinetics

B.15.3 Simulation (Aspen Plus) Hints

B.15.4 References

## Appendix C: Design Projects

### Project 1 Increasing the Production of 3-Chloro-1-Propene (Allyl Chloride) in Unit 600

C.1.1 Background

C.1.2 Process Description of the Beaumont Allyl Chloride Facility

C.1.3 Specific Objectives of Assignment

C.1.4 Additional Background Information

C.1.5 Process Design Calculations

Fluidized-Bed Reactor, R-601

Reference

### Project 2 Design and Optimization of a New 20,000-Metric-Tons-per-Year Facility to Produce Allyl Chloride at La Nueva Cantina, Mexico

C.2.1 Background

C.2.2 Assignment

C.2.3 Problem-Solving Methodology

C.2.4 Process Information

### Project 3 Scale-Down of Phthalic Anhydride Production at TBWS Unit 700

C.3.1 Background

C.3.2 Phthalic Anhydride Production

C.3.3 Other Information

C.3.4 Assignment

C.3.5 Report Format

### Project 4 The Design of a New 100,000-Metric-Tons-per-Year Phthalic Anhydride Production Facility

# **Table of Contents**

C.4.1 Background

C.4.2 Other Information

C.4.3 Assignment

C.4.4 Report Format

## **Project 5 Problems at the Cumene Production Facility, Unit 800**

C.5.1 Background

C.5.2 Cumene Production Reactions

C.5.3 Process Description

C.5.4 Recent Problems in Unit 800

C.5.5 Other Information

C.5.6 Assignment

C.5.7 Report Format

C.5.8 Process Calculations

Calculations for Fuel Gas Exit Line for V-802

Calculations for P-801

Vapor Pressure of Stream 3

Calculations for P-802

## **Project 6 Design of a New, 100,000-Metric-Tons-per-Year Cumene Production Facility**

C.6.1 Background

C.6.2 Assignment

C.6.3 Report Format

Index