

Chemical Engineering for Chemists



Richard G. Griskey

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ACS Professional Reference Book

American Chemical Society
Washington, DC



Library of Congress Cataloging-in-Publication Data

Griskey, Richard G., 1931–

Chemical engineering for chemists/
Richard G. Griskey.

p. cm.—(ACS professional reference
book)

Includes bibliographical references (p.
–) and index.

ISBN 0-8412-2215-0

I. Chemical engineering.

I. Title. II. Series.

TP145.G78 1996

660—dc20

96-21026

CIP

Photo on cover courtesy of Safety-Kleen Corp.

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PRINTED IN THE UNITED STATES OF AMERICA

About the Author



RICHARD G. GRISKEY, Institute Professor Emeritus of Chemistry and Chemical Engineering at Stevens Institute of Technology since 1992, was born in Pittsburgh, Pennsylvania. He received his B.S. in chemical engineering from Carnegie-Mellon University in 1951. He served in the U.S. Army Combat Engineers from 1951 to 1953 (19 months in the Far East during the Korean War). He was then awarded an M.S. and a Ph.D. from Carnegie-Mellon.

Griskey has served as a professor and administrator at many institutions, including the University of Cincinnati, Virginia Polytechnic Institute and State University, the University of Denver, New Jersey Institute of Technology, the University of Wisconsin—Milwaukee, the University of Alabama—Huntsville, Stevens Institute of Technology, and Vanderbilt University. Griskey has held every academic rank (including distinguished professor); he has been a department chair, dean of engineering, provost, and executive vice-president.

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Griskey has held visiting professorships at the University of São Paulo in Brazil, Monash University in Australia, and the Institut du Pétrole in Algeria and has been an invited lecturer for the Royal Society of Chemistry in England. In 1971, the National Academy of Science appointed him senior visiting scientist to Poland.

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Preface

The impact of chemistry on the world is immense. Its importance is realized in basic chemical and petroleum industries, as well as in high-technology areas such as energy, environmental, biochemical, biomedical, and advanced materials, which are rapidly shaping the future. Yet although it is obvious that chemistry is a necessary ingredient in our world, it has been less clear in academic circles what skills are needed by scientists and engineers employed in the chemical industry and government to be successful professional practitioners.

To better understand the problem of educational needs, let us first consider chemistry to be a continuum that ranges from theoretical science to the application of chemical principles in technology. A simplistic view of a professional's responsibility within the continuum would be that a chemist takes care of theory and a chemical engineer handles application. Unfortunately, this is not how the industrial world works: Individual chemists and chemical engineers often find themselves at various places in the continuum. Chemists' responsibilities many times include applications, and chemical engineers find that they require a sound knowledge of basic chemistry. Hence, it is apparent that the practicing chemical professional in industry and government requires a broad range of chemical knowledge.

Academic training of chemical engineers already acknowledges the need for a broad chemical education because it mandates that undergraduate students take significant course work in analytical, organic, and physical chemistry, all, incidentally, usually taught by the chemistry department at colleges and universities. Degree accreditation, which is a joint effort by the American Institute of Chemical Engineers (AIChE) and the Accreditation Board for Engineering and Technology (ABET), is not granted unless the chemistry requirements are met. Actually, the total credits of chemistry required by the chemical engineering degree far exceed the number normally required for a chemistry minor in most liberal arts programs. The additional applied chemistry courses, such as thermodynamics and kinetics, that are taken by the engineering students make it even more evident that the holder of a baccalaureate in chemical engineering has an exceptionally strong chemistry background.

The inverse, that the academic training of chemists requires a significant number of courses in chemical engineering, is not the case except in certain countries in

continental Europe. The lack of engineering courses causes problems for the chemist when he or she ends up in an applications area of the chemistry continuum.

However, the problem can be alleviated by providing chemical professionals with sufficient chemical engineering background, knowledge, and wherewithal that enable them to realize their full potential.

THE APPROACH OF THIS BOOK

Chemists already have a theoretical grounding in many topics that engineers are trained to apply, so the approach of this book is to start with what chemists know and add relevant principles to them. I do not seek to teach a new approach to a skill that chemists already possess. Chemists, for example, learn stoichiometry and certain aspects of thermodynamics, chemical equilibrium, and chemical reaction kinetics. I have chosen to concentrate on new principles and move them from the theoretical to the semiempirical to the empirical approaches needed to use them.

I have selected my approach based on my past experience gained from teaching chemical engineering to chemists. Some people might argue that chemists should take all of the chemical engineering courses they have not had, but I believe that chemists already have a strong background in many of the topics covered in introductory chemical engineering courses. I did not always believe this. While at the University of Denver in the late 1960s, I initiated and taught a graduate course titled "Chemical Engineering for Scientists". One part of the course called for me to teach the students how to do mass balances. I handed out a set of homework problems of the sort that are typical in an engineering course, requiring them to be done by the next class.

At the next meeting, I collected the homework and began to go over the problems. As I did so, the students in the class wore perplexed expressions that changed to surprise when I obtained the correct answer. Sensing that something was out of order, I asked the group what was wrong. Their collective response was, "We've never seen anyone do a mass balance that way." I asked one of them to work the problem at the board, upon which *I* looked perplexed and surprised when the student got the correct answer.

The obvious lesson I learned is that chemists, as do scientists and engineers, thoroughly understand basic mass balances and do not have to learn stoichiometry. Similarly, other topics such as chemical equilibrium are understood in much the same way. Therefore, this text, while it touches on these subjects, will do so only as a brief review and exposure to the chemical engineering approach.

HOW THIS TEXT CAN HELP YOU

The selection of topics used in this book was derived from my experience working with chemists in industry, from my teaching and research activities, and, last but not least, from my interactions with more than 4000 professionals who have taken my three-day course, Chemical Engineering and Process Fundamentals for Chemists, sponsored by the American Chemical Society. The last experience has been especially useful in shaping the text and has provided insight as to how powerful chemical engineering knowledge can be in enhancing one's career. A few examples reported by some of the course alumni will demonstrate this point:

- One individual who came to the class was the supervisor of a large number of professionals (half were chemists and half engineers). The engineers, the supervisor said, were using the supervisor's lack of process knowledge to their advantage, using engineering jargon during meetings and generally making things difficult. After taking the course, the supervisor was able to understand what the engineers were discussing and was, in fact, able to ask more perceptive and applicable questions and to control meetings with more authority. Understanding engineering basics leveled the playing field.
- Another class attendee was a researcher who had large amounts of interesting data that had defied interpretation. A knowledge of how to apply dimensionless groups of numbers to data from different scales of operations (a technique commonly used by chemical engineers) gave this individual the means to both comprehend the significance of the data and the ability to write three refereed journal articles.
- A third person was transferred to a pilot plant group after taking the course. This individual said that the understanding of chemical engineering basics (i.e., heat transfer and reactor design) made it possible to perform on a level orders of magnitude above the precourse level.

There is general consensus among course attendees that they were able to handle a wide range of process situations and problems. Furthermore, everyone agreed that technical communication and jargon problems disappeared.

HOW TO USE THIS BOOK

Each chapter contains examples of problems and their complete solutions, the complexity of which should not be a problem to any chemist, scientist, or engineer who has had calculus. (Most of the problems require more algebra than calculus.) And finally, references and further reading sources are provided at the end of each chapter.

I suggest that you read Chapters 1 through 6 in order because each subsequent chapter builds on the concepts of the previous one. Working through the solved examples in each chapter is extremely helpful. Above all, try to develop a physical sense of the meaning of the materials.

Finally, this text is just a start, not an end. There is a Chinese proverb that says, "A journey of a thousand miles begins with a single step." It is my hope that this text will provide many steps along the journey toward an understanding of chemical engineering principles and applications, a journey that will bring you to an even higher level of professional competence.

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Contents

Preface	xv
Chapter 1. Introduction to Chemical Engineering Principles	1
Interface Between Chemistry and Chemical Engineering	1
What's in This Book	2
Mass Balances	2
Example 1.1. Mass Balance Across a Storage Tank	3
Example 1.2. Applying Multiple Boundaries	4
Energy Balances	6
Heat Transfer in Industrial Chemical Processes	6
Temperature Effect on Reaction Rates	6
Effect of Heat Transfer on Reaction Completion	7
The Nonisothermal Reactor as an Industrial Standard	9
Heat Transfer Equipment	9
Heat Transfer Knowledge for Optimization	9
Fluid Flow and Chemical Processing	11
Mass Transfer in Separation, Purification, and Heterogeneous Systems	15
Examples of Mass Transfer	15
Chemical Engineering Kinetics, Process Control, and Engineering Economics	17
Chemical Engineering Kinetics	17
Process Control	18
Engineering Economics	18
Basic Steps for Scaling Up a Process Design	19
The Principles of Fluid Flow, Heat Transfer, and Mass Transfer	19
Chemical Engineering Principles Applied to New Technologies	20
Chapter 2. Applied Thermodynamics	23
Terms	23
Temperature and Heat	24
Definition of Work	24
Conservation of Energy—The First Law of Thermodynamics	25
Enthalpy	26
Phase Behavior	27
Estimating Two-Phase Thermodynamic Properties	29
Equations of State	29
Thermodynamic Functions	30
Specific Heat at Constant Volume	30
Specific Heat at Constant Pressure	31

Specific Heats for Other Work Modes.....	31
Relationships Between Thermodynamic Functions for an Ideal Gas.....	31
Computing Thermodynamic Functions for Real Gases	34
Example 2.1. Work, Internal Energy, and an Ideal Gas	36
Example 2.2. Applying the Theory of Corresponding States	39
Example 2.3. Applying the Theory of Corresponding States	40
Applying the First Law to Flows of Both Mass and Energy.....	41
Example 2.4. Adiabatic Flow and a Two-Phase Mixture	42
Example 2.5. Accounting for Mechanical Work.....	43
The Second Law of Thermodynamics—The Limits of Efficiency.....	44
Defining Engine Efficiency—The Carnot Cycle	44
Entropy.....	46
Example 2.6. Evaluating the Performance of a Refrigerator	48
Example 2.7. Efficiency Losses of a Turbine	50
Gibbs Free Energy, Chemical Potential, Fugacity, and Activity.....	51
Applied Phase Equilibrium and the Distribution Coefficient.....	54
Example 2.8. Calculating Distribution Coefficients.....	60
Activity Coefficients.....	62
Example 2.9. Applying the Redlich–Kister Equation.....	65
Chapter 3. Fluid Flow	69
Fluid Statics	69
Example 3.1. Determining Pressure with a Manometer	70
Example 3.2. Static Pressure in a Tank.....	71
Buoyancy.....	72
Example 3.3. Calculating Buoyancy	72
Fluid Dynamics—The Character of Flowing Fluids.....	73
What Reynolds Found.....	73
The Reynolds Number—A Dimensionless Comparison of Flows	73
Flow and the First Law of Thermodynamics—Bernoulli’s Equation	74
Example 3.4. Flow Due to Head Pressure.....	75
Example 3.5. Flow Due to Density Differences	76
Frictionless Flow Measurement Devices.....	77
Example 3.6. Measuring Flow with an Orifice Plate	79
Friction Losses in Fluid Flow.....	80
Friction in Laminar Flow	81
Friction in Turbulent Flow.....	82
Example 3.7. Calculating Laminar Air Flow	88
Example 3.8. Calculating the Pressure Drop of Liquid Flow.....	89
Example 3.9. Sizing a Pump	89
Types of Pumps and Their Uses	91
Example 3.10. Using a Modified Friction Factor Chart	93
Example 3.11. Calculating Flow from a Ruptured Pipe	94
Flow Around Submerged Objects—Calculating a Drag Force.....	96
Characterizing Flow	96
Example 3.12. Calculating the Settling Rate of Fine Droplets.....	97
Non-Newtonian Fluid Flow	98


Mixing Fluids.....	99
Power Requirements	99
Example 3.13. Calculating the Power Needed To Agitate a Liquid.....	103
Flow Through Packed Beds, Porosity, and Sphericity.....	105
Chapter 4. Heat Transfer.....	109
Conduction.....	109
Convection—Heat Transfer with Motion.....	110
Radiation—Heat Transfer Through a Vacuum.....	110
Steady-State Heat Conduction— q Steady with Time	110
Example 4.1. Heat Transfer Through a Composite, Flat Surface	112
Example 4.2. Heat Transfer Through a Cylinder.....	113
Steady-State Heat Conduction with a Heat Source—Heated Wires, Chemical Reactors, and Phase Changes.....	113
A Source of Heat	113
Example 4.3. Heat Transfer from a Wire	114
Unsteady-State Heat Conduction.....	114
Changes with Time	114
Example 4.4. Unsteady-State Heating of a Slab	115
Convective Heat Transfer—Forced and Free	116
Dimensionless Number for Comparing Conduction and Convection— The Nusselt Number.....	117
The Overall Heat Transfer Coefficient, U —Combining Conductive and Convective Heat Transfer Effects	118
Design Equations for Convective Heat Transfer.....	119
Example 4.5. Calculating the Heat Transfer Coefficient h	120
Example 4.6. Heating a Viscous Fluid.....	121
Example 4.7. Calculating U for an Annular Heat Exchanger.....	122
Heat Transfer with Flow Around Objects	124
Example 4.8. Heat Transfer Across In-Line Tubes	126
Heat Transfer of a Condensing Film	128
Heat Transfer of Condensing Droplets.....	129
Heat Transfer Due to Vaporization.....	130
Example 4.9. Condensation Heat Transfer	132
Example 4.10. Condensation on a Bank of Tubes	133
Radiative Heat Transfer.....	133
How an Object’s Shape Affects Radiation.....	134
Example 4.11. Radiation Between Parallel Black Bodies.....	135
Example 4.12. Radiation to a Cylinder.....	136
An Introduction to Heat Exchangers	137
Criteria for Designing Heat Exchangers	138
Designing Heat Exchangers—Compensating for Temperature and Configurations	139
Chapter 5. Mass Transfer.....	147
Steady-State Molecular Diffusion	149
Mass Transfer.....	149
Example 5.1. Steady-State Molecular Diffusion Through a Slab	151

Unsteady-State Molecular Diffusion—Time Dependence	153
Mass Transfer at a Phase Boundary	154
Mass Transfer for Different Geometries	155
Example 5.2. Sublimation Rate from a Cylinder.....	160
Example 5.3. Evaporation Rate from a Droplet.....	161
Equilibrium Stage Operations, the Ideal Stage, and Phase Equilibria	163
Mass Balances for an Ideal Stage	163
Energy Balance for an Ideal Stage.....	169
The McCabe–Thiele Method	170
Example 5.4. Designing a Fractionating Column with Different Feed Conditions.....	171
Minimum and Maximum Stages in an Ideal Stage Separation.....	173
Relative Volatility—Using Enthalpy–Concentration Diagrams.....	174
The Ponchon–Savarit Method of Nonconstant Molal Mass Transfer	175
Estimating the Stages Needed for a Multicomponent Separation with Relative Volatilities	176
Differential Distillation for a Batch Distillation	177
Extractive Distillation—Adding a Third Component To Improve Volatilities.....	178
Graphical Solution of Absorption in a Plate Column	180
Example 5.5. Graphical Estimation of the Number of Stages Needed for an Extraction	181
Packed Column Absorption	183
Example 5.6. Estimating the Packed Column Height Needed for Absorption.....	187
Case 1. Detailed Solution	188
Case 2. Using an Analytical Technique	189
Case 3. Using Figure 5.38.....	189
Extraction.....	189
Ideal and Real Stages and Stage Inefficiencies	193
Mechanical Separation Processes	193
Filtration	196
Centrifugation	199
Chapter 6. Applied Reaction Kinetics and Reactor Design	205
A Review of Chemical Kinetics and Chemical Equilibrium	205
Relationship of Activity to Fugacity	207
Example 6.1. Calculating Equilibrium Concentrations, Given K	207
Reaction Order and Effect of Temperature on Reaction Rate.....	208
Chemical Reaction Kinetics Categories	209
Homogeneous, Isothermal, Uncatalyzed Reaction Kinetics	210
Example 6.2. Calculating the Reaction Order, Specific Reaction Rate, and the Half-Time of the Reaction	211
Calculating by Differentiation	213
Calculating by Integration	213
Calculating by the Half-Time Method	214
Calculating the Rate When the Reaction Order Is Known.....	214
Example 6.3. Calculating the Reaction Rate and Percent Conversion When the Reaction Order Is Known	216

Example 6.4. Calculating Conversion Versus Time and Equilibrium	
Conversion for a Reversible Reaction	219
Example 6.5. Working with Simultaneous Reactions.....	220
Homogeneous, Isothermal, Catalyzed Reaction Kinetics	221
Liquid-Phase Reactions—Acid–Base Catalysis	221
Gas-Phase Reactions.....	222
Homogeneous, Nonisothermal, Uncatalyzed Reaction Kinetics	223
Adiabatic Reactor.....	223
Isothermal Reactor with Heat Transfer	224
Nonadiabatic, Nonisothermal Reactor.....	225
Example 6.6. Homogeneous, Nonisothermal, Nonadiabatic Reaction	
Calculations—A Trial-and-Error Technique	225
Example 6.7. Adiabatic, Isothermal Reaction Calculations	227
Heterogeneous, Isothermal, Uncatalyzed Chemical Kinetics and the	
Influence of Mass Transfer	229
Heterogeneous, Isothermal, Catalyzed Reactions—Surface	
Reaction Dependency	231
Chemical Reactor Design	234
Tubular Flow Reactors.....	235
Volume Determination—Residence Time and Space Velocity	235
Example 6.8. Calculating Tubular Reactor Volume	
for a First-Order, Irreversible Reaction	238
Example 6.9. Calculating the Reactor Volume Needed	
for a Reversible Reaction with Integration or Graphing	239
Friction Considerations.....	240
Effect of Laminar Flow on Reactor Design.....	242
Nonisothermal Conditions and Flow Reactors	243
Example 6.10. Nonisothermal Tubular Reactor Volume	
Calculations Require a Trial-and-Error Solution	243
Continuous-Flow Stirred Tank or Steady-State Reactors	245
Example 6.11. Calculating Concentrations and Reactor Volumes	
for a Reversible Reaction via a Graphical Method	250
Unsteady-State or Semibatch Reactors—Analytical and	
Estimation Techniques	253
Example 6.12. Calculating the Reaction Completion over Time	
Requires Iterations on a Computer	254
Gas–Solid Reactors.....	254
Fixed-Bed Reactors	254
Fluidized-Bed Reactors.....	255
Example 6.13. Evaluating the Performance of a Fluidized Bed.....	256
Types and Advantages of Gas–Liquid Reactors.....	257
Chapter 7. Process Control and Data Acquisition	261
Control Applications and Types of Systems	261
Minimizing and Regulating External Disturbance	262
Creating Stability	262
Optimizing Production of Product	262

Types of Control	262
Basics of Control Systems.....	263
Feedback Control.....	263
Types of Control Actions.....	264
Feedforward Control.....	266
Process Control Equipment.....	267
Measuring Elements.....	267
Control Elements.....	269
Selection Criteria for Control Valves.....	270
Process Dynamics—Determining Control Response Mathematically.....	270
Laplace Transforms.....	271
Forcing Functions—A Method of Checking a Feedback Loop.....	273
Process Dynamics Design Methods.....	274
Routh–Hurwitz Criterion.....	275
Bode Plot.....	275
Nyquist Plot.....	276
Cohen–Coon Method.....	278
Additional and Advanced Control Methods.....	278
Data Acquisition by Computer.....	280
Chapter 8. Engineering Economics and Process Design	283
Time Value of Money.....	283
Interest, the Cost of Money.....	284
Replacement Cost Estimation.....	284
Depreciation and Salvage Value: Depreciation Methods and Sinking Funds.....	285
Economic Alternatives.....	286
Example 8.1. Estimating Equipment Replacement Costs.....	286
Example 8.2. Estimating the Present Value of Equipment.....	287
Guidelines for Comparing Investment Alternatives.....	287
Example 8.3. Comparing the Incremental Costs of Alternatives.....	288
Example 8.4. Comparing the Incremental Costs of Multiple Units.....	288
Example 8.5. Comparing Complex Investments Using Several Methods.....	289
Cost Indexes—Estimating Process Costs from Existing Operations.....	292
Example 8.6. Estimating the Cost of a New Unit Based on the Cost of an Old One.....	292
Equipment Cost—Capacity and Scaling Factors, Six-Tenths Rule.....	293
Sources of Capacity Cost Data.....	293
Using Scaling Factors To Estimate Equipment Costs.....	293
Example 8.7. Using Indexes To Estimate Costs.....	294
Example 8.8. Using Scaling Factors To Estimate Costs.....	296
Capital Investment Estimating Techniques.....	296
Data for Estimating Costs Based on Percentages.....	296
Estimating Costs Based on Multiples of Known Costs.....	297
Using Power Factors for Estimation.....	297
Turnover Ratio—Order of Magnitude Estimates.....	299
Pricing Chemical Products.....	299

Process Design	301
Research Phase.....	301
Feasibility Studies	301
Process Development	302
Process Design.....	302
Construction and Operation	302
Conclusion	303
Appendix A. Dimensionless Groups and Scale Factors	305
Appendix B. Physical Properties	307
Appendix C. Symbols	319
Index.....	327



Introduction to Chemical Engineering Principles

INTERFACE BETWEEN CHEMISTRY AND CHEMICAL ENGINEERING

Chemistry and chemical engineering, though taught as separate disciplines, are parts of the fabric that is chemical science and technology. Although they are closely related, chemistry and chemical engineering do differ.

Chemistry came first in the cultures of many nations from the earliest times. Chemical engineering came later when the large, complex production during the Industrial Revolution (18th and 19th centuries) demanded skills beyond those offered by chemistry or traditional engineering education. Fluids, previously transported on a small scale in buckets or flasks, needed to be moved by piping and pumps. Heat could no longer be supplied by throwing another log on the fire. Industrial production needed the help of an engineer.

At first, a mechanical engineer seemed to have the knowledge to make large-scale processes possible. But mechanical engineering could not provide the technology needed because it was divorced from chemistry. Mechanical engineers worked with mass. The mole was a foreign concept to them, and molecular weight was as close as they came to chemistry. There was a chasm between chemists and mechanical engineers.

The chemical industry needed engineers familiar with chemistry and production, so chemical engineering was born. At first, chemical engineering was a branch of chemistry, just as organic, physical, inorganic, and analytical chemistry were established. During the Industrial Revolution, however, chemistry was undergoing a major change, developing into a science in which it was necessary to know the whys as much as the hows. Chemistry moved toward elucidating fundamentals and away from applications.

Today chemistry continues to move toward fundamentals, and this development puts chemists at a disadvantage in dealing with industrial processes. The physical chemistry course is an example of chemistry's concentration on fundamentals. Less than 20 years ago, it included treatment of the laws of thermodynamics, solution behavior, phase equilibrium, chemical kinetics, and diffusion phenomena, all applicable to designing and operating industrial processes. In many universities today, however, physical chemistry is dedicated mainly to statistical and quantum mechanics. Applied chemistry is now taught mainly in the engineering curriculum.

WHAT'S IN THIS BOOK

We're in another revolution now. New materials, new industries, and changing economics demand engineering skills from chemists, scientists, and researchers uneducated in engineering. With the proliferation of small technical companies, many classically trained scientists wear the hats not only of the discoverer of a new material, but also of the manager in charge of producing it commercially.

If you're reading this book, you've realized you need some practical engineering skills. This chapter summarizes the principal areas in chemical engineering that will enable you to understand and work successfully in a chemical plant, pilot plant, product development group, or scale-up project.

It is divided into chapters that concentrate on applied thermodynamics, fluid flow, heat transfer, mass transfer, chemical engineering kinetics, process design and control, and engineering economics. Each chapter presents a discussion of fundamentals with a large number of examples and their solutions. The approach should give you a firm grasp of basic principles and the ability to solve practical problems.

MASS BALANCES

An initial course in chemical engineering usually covers mass balances, familiar to chemists as stoichiometry. A mass balance represents nothing more than the Law of Mass Conservation, i.e., what goes into a system must come out or accumulate. On an industrial scale, mass is balanced across entire processes. It is one of the first tasks an engineer undertakes in designing or optimizing a process.

To obtain a mass balance, apply the following systematic approach:

1. Make a schematic flow diagram of the process, showing all process streams flowing into and out of the system, being sure to include recycled and side streams.
2. Note all of the physical and chemical changes taking place, and list all available data about the streams, including flow rates, temperatures, and pressures.
3. Choose a basis for the mass balance calculation (moles or mass) and a time period over which the balance will be calculated.
4. Select the process segment of interest and circle it to establish the streams entering and leaving. This circle is called the *boundary*. Process streams that do not cut the boundary, including recycled flows, are not considered in the mass balance calculations.
5. Develop equations that describe relationships between entering and exiting streams and enable you to calculate the mass balances across the schematic.

You may need to develop several independent equations, one for each unknown variable. Sometimes in complex systems, many components are interrelated, greatly reducing the number of independent equations.

- To solve the mass balance, track a compound or compounds through the chosen process segment. If a chemical reaction occurs, track an element or a radical.

Solutions for mass balance problems cannot be generalized and are handled by understanding the process. Because of the lack of generalization possible, this book does not devote a chapter to mass balancing. Instead, the mass balances shown in Examples 1.1 and 1.2 will get you started, and special situations in mass balancing will be noted in chapter examples hereafter.

Example 1.1 demonstrates the principle of mass balance, the interaction of input, output, and accumulation.

Example 1.2 illustrates several important mass balance techniques. The first technique shows how to track specific components through a process, rather than characterizing the overall mass flow. The second technique shows how to define the boundary for a mass balance; only those process streams within the boundary are considered in the mass balance calculations. Furthermore, we'll see that you can define as many boundaries as you need to solve the balance of a given situation.

EXAMPLE 1.1. MASS BALANCE ACROSS A STORAGE TANK

A half-full 60,000-gallon gasoline storage tank is filled from five sources in one day. These sources supply 8,000, 7,000, 5,000, 13,000, and 19,000 gallons, respectively. During the day, 57,000 gallons of gasoline are withdrawn. What is the final volume of gasoline in the tank?

The mass balance is solved by following the six steps previously described. The schematic for the first step is a sketch of a tank showing five input and one output streams. No chemical changes take place, only changes in flow. The mass balance is in gallons and the time interval is one day.

The law of conservation is

$$\Sigma m_{\text{input}} = \Sigma m_{\text{output}} + \Sigma m_{\text{accumulation}}$$

for which m is the mass or moles. (When there is no accumulation of flow, the system is operating under *steady-state* conditions. The accumulation here represents unsteady-state conditions.) The basis for this calculation is mass. To convert the units in gallons to mass, we apply

$$m = V\rho$$

where V is volume and ρ is the density of gasoline in weight per unit volume. The mass balance can then be stated:

$$\rho_{\text{input}}\Sigma V_{\text{input}} = \rho_{\text{output}}\Sigma V_{\text{output}} + \rho_{\text{accumulation}}\Sigma V_{\text{accumulation}}$$

If

$$\rho_{\text{input}} = \rho_{\text{output}} = \rho_{\text{accumulation}}$$

then,

$$\Sigma V_{\text{input}} = \Sigma V_{\text{output}} + \Sigma V_{\text{accumulation}}$$