

FUNDAMENTALS OF  
ENGINEERING  
THERMODYNAMICS





**MICHAEL J. MORAN**

The Ohio State University

**HOWARD N. SHAPIRO**

Iowa State University of Science and Technology

Acquisitions Editor	Joseph Hayton
Marketing Manager	Katherine E. Hepburn
Production Editor	Sandra Russell
Cover and Text Designer	Madelyn Lesure
Cover Illustration	Roy Wiemann
Illustration Editor	Sigmund Malinowski
Illustrations	Precision Graphics, Inc.

This book was typeset in 10/12 Times Roman by The PRD Group, Inc. and printed and bound by Von Hoffmann Press, Inc. The cover was printed by Phoenix Color Corp. Inc.

The paper in this book was manufactured by a mill whose forest management programs include sustained yield harvesting of its timberlands. Sustained yield harvesting principles ensure that the number of trees cut each year does not exceed the amount of new growth.

This book is printed on acid-free paper. ∞

Copyright © 1988, 1992, 1996, 2000 by John Wiley & Sons, Inc. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (508) 750-8400, fax (508) 750-4470. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc. 605 Third Avenue, New York, NY 10158-0012, (212) 850-6008, E-mail: PERMREQ@WILEY.COM. To order books or for customer service call 1-800-CALL-WILEY (225-5945).

***Library of Congress Cataloging in Publication Data:***

Moran, Michael J.

Fundamentals of engineering thermodynamics/Michael J. Moran,  
Howard N. Shapiro.—4th ed.

p. cm.

ISBN 0-471-31713-6 (cloth : alk. paper)

1. Thermodynamics. I. Shapiro, Howard N. II. Title.

TJ265.M66 1999

621.402'1—dc21

99-26489

CIP

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

In this fourth edition we have retained the basic objectives of the first three editions:

- to present a thorough treatment of engineering thermodynamics from the classical viewpoint,
- to provide a sound basis for subsequent courses in fluid mechanics and heat transfer,
- to prepare students to use thermodynamics in engineering practice.

Enough material is provided in this book for an introductory course in engineering thermodynamics and for a follow-up course dealing mainly with applications. The text is also suitable for survey courses for majors or non-majors. A background in elementary physics and calculus is presumed.

While the fourth edition retains the basic organization and level of the previous editions, we have introduced several enhancements proven to facilitate student learning. Included are new text elements and interior design features that help students read and study the subject matter. Further, in recognition of the importance and increased role of computer software in engineering practice, we have incorporated the use of the software *Interactive Thermodynamics: IT* into the text in a manner that allows instructors to use software in their courses. However, the presentation is structured to allow those who prefer to omit the software material to do so easily.

## NEW IN THE FOURTH EDITION

- New elements to enhance student learning:
  - Each chapter begins with a clear statement of the chapter objective.
  - Key words are listed in the margins and coordinated with the text material.
  - Methodology Update* in the margin identifies where we refine our problem solving methodology.
  - Each chapter concludes with a *Chapter Summary* and *Study Guide* accompanied by a list of key terms to help students study the material.
  - Each chapter has a set of discussion questions under the heading *Things to Think About* that may be answered on an individual or group basis to develop a deeper understanding of the text material, foster critical thinking, and test understanding.
  - Numerous informal examples throughout the text have been identified with the opening phrase **For Example...** These supplement 141 more formal examples that feature our solution format.
  - More subheadings and chapter subdivisions are included to guide students through the material.
  - Text figures now provide more realistic representations of real-world engineering systems.
- Integration of *Interactive Thermodynamics: IT* for instructors who choose to use software in their courses:
  - Brief tutorials of *IT* features are included at carefully selected locations in the text. The tutorials are supplemented by a User's Manual provided with the software disc.

- IT* is used selectively in solved examples to illustrate how software can be applied effectively to enhance understanding or to solve more complex problems.
- Many end-of-chapter problems now include a final part involving *IT* that extends the solution and/or encourages further investigation. Problems that include parts for which software use is suggested are identified by a special computer icon. However, these problems also can be solved conventionally in most cases without using software.
- Other new features:
  - Several new formal examples having broad appeal are included to address common points of difficulty for students.
  - Solved examples, key equations, and selected discussions are clearly set off, and a special device is used to help students identify unit conversions.
  - The end-of-chapter problems have been significantly revised, and problems are now classified under headings to expedite problem selection.
  - The design and open-ended problems also have been revised significantly.
  - Owing to the phase-out of chlorofluorocarbon refrigerants and a growing interest in *natural* refrigerants, the Refrigerant 12 property tables have been replaced with propane tables.
  - The discussion of transient analysis has been expanded.
  - The ideal gas tables have been redesigned for ease-of-use, and a table of hydrocarbon heating values has been provided.
  - To be consistent with global practice, the term *availability* has been replaced with *exergy*, and the symbols have been changed accordingly.
  - The material on engineering design and thermoeconomics has been updated.

## SOFTWARE AND SUPPLEMENTS

***Interactive Thermodynamics: IT.*** The computer software tool *Interactive Thermodynamics: IT* provides an important adjunct to learning engineering thermodynamics and solving engineering problems. The program is built around an equation solver enhanced with thermodynamic property data and other valuable features. Using *IT*, students can obtain a single numerical solution and investigate the effects of varying parameters. Graphical output can be obtained, and the Windows-based format allows the use of any Windows word-processing software or spreadsheet to generate reports. Other features of *IT* include:

- a guided series of help screens and a number of solved examples from the text to help learn how to use the program.
- drag-and-drop templates for many of the standard problem types, including a list of assumptions that can be customized to the problem at hand.
- predetermined scenarios for power plants and other important applications.
- thermodynamic property data for water, refrigerants 22 and 134a, ammonia, propane, air–water vapor mixtures, and a number of ideal gases.
- the capability to input user-supplied data.
- the capability to interface with user-supplied routines.
- a User’s Manual that expands on the text discussions of *IT*.

We believe that software is best used as an *adjunct* to the problem-solving process, and that the equation-solving capability of the program cannot substitute for careful engineering analysis. Accordingly, the software is structured so students still must develop models and analyze them, perform limited hand calculations, and estimate

ranges of parameters and property values before moving to the computer to obtain solutions and explore possible variations.

The software is available as a stand alone item or packaged with this text at a significant discount. Contact your local John Wiley & Sons representative for details.

**Supplements.** The following supplements are available to adopters:

- Student access to the Thermo Design Online Website: *www.wiley.com/college/thermo*. This innovative site is designed to link classroom learning to industry practice. Students will have access to information that supports the design and open-ended problems, information on companies where thermodynamic principles are applied, and additional links to sites of interest in engineering thermodynamics.
- An Instructor's CD has been developed that contains electronic copies of figures from the text. These figures are suitable for producing transparencies for classroom use. Also included on the CD are solutions to end-of-chapter *IT* problems and sample course syllabi.
- Additional resources and book updates are available through *www.wiley.com/college/moranshapiro*.
- Our popular comprehensive *Instructor's Manual* has been fully updated for the fourth edition. The manual includes fully developed solutions to all end-of-chapter problems, sample syllabi, and authors' comments on the design and open-ended problems. Available to instructors upon written request to the publisher, or contact your local John Wiley & Sons representative.
- Also available are booklets containing the appendix tables, figures, and charts for student use during closed-book examinations.

## FEATURES RETAINED FROM THE THIRD EDITION

- A clear and concise presentation.
- A problem-solving methodology that encourages systematic thinking.
- A thorough development of the second law of thermodynamics, featuring the entropy production concept.
- An up-to-date presentation of exergy analysis, including an introduction to chemical exergy.
- Sound developments of engineering thermodynamics applications, including power and refrigeration cycles, psychrometrics, and combustion.
- A generous selection of end-of-chapter problems.
- Design and open-ended problems provided under a separate heading at the close of each chapter.
- Flexibility in units, allowing either an SI or a mixed SI/English presentation.

This book has evolved over many years of teaching the subject matter at both the undergraduate and graduate levels. Clear and complete explanations together with numerous well-explained examples make the text user-friendly and nearly self-instructive. This frees the instructor from lecturing exclusively and allows class time to be used in other beneficial ways. Our aim has been a clear and concise presentation without sacrificing completeness. We have attempted to make the material interesting and easy to read. Favorable evaluations from both instructors and students who have used the previous editions in a wide range of engineering programs indicate that these objectives have been met.

**Systematic Approach to Problem Solving.** One of our primary goals in this textbook is to encourage students to develop an orderly approach to problem solving. To this end, a formal problem analysis and solution format that helps students think systematically about engineering systems is used throughout the text. Solutions begin by listing assumptions and proceed step-by-step using fundamentals. Solutions are annotated with comments that identify key aspects of the solution. Unit conversions are explicitly included when numerical evaluations are made. The solution methodology is illustrated by 141 formal examples, which are set apart from the main text so they can be easily identified. The methodology we use is compatible with those of two other well-established Wiley titles: *Fundamentals of Heat and Mass Transfer* by F. P. Incropera and D. P. De Witt and *Introduction to Fluid Mechanics* by R. W. Fox and A. T. McDonald. With this choice of solution format, a series of three books similar in presentation, level, and rigor are available that cover the core thermodynamics, fluid mechanics, and heat transfer sequence common to many curricula.

**Thorough Development of the Second Law.** As there is greater interest today in entropy and exergy (availability) principles than ever before, a thorough development of the second law of thermodynamics is provided in Chapters 5, 6, and 7. The importance of the second law is conveyed throughout by stressing its relevance to the goal of proper energy resource utilization. A special feature is the use of the entropy production concept that allows the second law to be applied effectively in ways readily mastered by students (Chapter 6). Another special feature is an up-to-date introduction to exergy analysis, including exergetic efficiencies (Chapter 7). Chemical exergy and standard chemical exergy are also introduced and applied (Chapter 13). Entropy and exergy balances are introduced and applied in ways that parallel the use of the energy balances developed for closed systems and control volumes, unifying the application of the first and second laws. Once introduced, second law concepts are integrated throughout the text in solved examples and end-of-chapter problems. The presentation is structured to allow instructors who wish to omit exergy analysis to do so.

**Emphasis on Applications.** Emphasis has been placed on sound developments and careful sequencing of the application areas. Chapters 8 to 14, dealing with applications, allow some flexibility in the order and the amount of material covered. For example, vapor and gas power systems are discussed in Chapters 8 and 9, and refrigeration and heat pump systems are the subject of Chapter 10. But instructors who prefer to treat all vapor cycle material at one time can include vapor-compression and absorption refrigeration with Chapter 8. Advanced and innovative energy systems, such as cogeneration systems, combined power cycles, and cascade refrigeration cycles, are incorporated in Chapters 8 to 10 where they fall appropriately and are not relegated to a catchall chapter. As the study of gas flows falls naturally with the subject of gas turbines and turbojet engines, an introduction to one-dimensional compressible flow has been included in Chapter 9. The chapters dealing with applications provide illustrations of the use of exergy principles.

**Wide Variety of End-of-Chapter Problems.** More than 40 percent of the over 1400 end-of-chapter problems have been replaced or revised. Problems are now classified under headings to expedite problem selection. The problems are sequenced to correlate with the subject matter and are generally listed in increasing order of difficulty. They range from confidence-building exercises, which illustrate basic concepts, to more challenging problems, which may involve systems with several components. A special effort has been made to include problems that involve higher-order and critical thinking. Students are asked to construct plots, analyze trends, and discuss what they observe, which enhances their analytical skills and fosters the development of engineering judgment. A number of problems are included for which the use of a computer is recommended. These are identified by a computer icon.

The *Instructor's Manual* accompanying the textbook provides solutions to all end-of-chapter problems in the same format as used in the formal solved examples. Solutions may be photocopied for posting or preparing transparencies for classroom use, eliminating the drudgery of problem solving for the instructor. Also provided are sample syllabi for two-course sequences and one-term survey courses in engineering thermodynamics on both semester and quarter bases. Owing to the nature of design and open-ended problems, the *Instructor's Manual* provides only brief discussions and/or literature references to assist instructors in guiding students to achieve *individual* outcomes for those problems.

**Emphasis on Design.** Continuing our emphasis on the design component of engineering curricula from the previous editions, we have enhanced the design aspects of the presentation even further. Over one-third of the design and open-ended problems included at the end of each chapter have been revised. Also, updated material on engineering design and thermoeconomics is provided in Section 1.7: *Engineering Design and Analysis* and Section 7.7: *Thermoeconomics*. In Section 1.7, we emphasize that design by nature is an exploratory process and readers should not expect design problems to have a single, clearly identifiable answer. Rather, constraints must be considered in seeking the best answer from among a number of alternatives. Section 7.7 brings in the important issue of economic constraints in design. The topic is introduced to students in the context of design, and fits naturally with the treatment of exergy in Chapter 7, where irreversibilities are associated with cost.

**Realistic Design and Open-Ended Problems.** The fourth edition includes 140 *design and open-ended problems*, ten per chapter. These problems provide brief *design experiences* that afford students opportunities to develop their creativity and engineering judgment, formulate design task statements, apply realistic constraints, and consider alternatives. The primary emphasis of the design and open-ended problems is on the subject matter of the text, but students may have to do some collateral reading before a solution can be developed. Instructors may elect to narrow the focus of the problems to allow individual students to achieve a result with a relatively modest expenditure of effort or may decide to use the problems as points of departure for more extensive group-type projects. An important feature of many of the design and open-ended problems is that students are explicitly required to develop their communications skills by presenting results in the form of written reports, memoranda, schematics, and graphs.

**Flexibility in Units.** The text has been written to allow flexibility in the use of units. It can be studied using SI units only, or using a mix of SI and English units. Well-organized tables and charts are provided in *both* sets of units. Proper use of unit conversion factors is emphasized throughout the text. In this edition, unit conversion factors are set off by a special device to help students identify unit conversions. The force–mass conversion constant  $g_c$  is treated as implicit, and equations involving kinetic or potential energy are handled consistently, regardless of the unit system used.

**Other Aspects.** The text has several other special aspects. Among these are:

- The development of the first law of thermodynamics in Chapter 2 begins with energy and work concepts familiar to students from earlier physics and engineering mechanics courses and proceeds operationally to the closed system energy balance. Thermodynamic cycles are introduced in Chapter 2, together with the definition of the thermal efficiency of power cycles and coefficients of performance of refrigerators and heat pumps. This permits elementary problem solving with cycles using the first law before cycles are considered in depth in later chapters.

- Property relations and data for pure, simple compressible substances are introduced in Chapter 3 *after* the energy concept has been developed in Chapter 2. This arrangement has the following advantages:
  - it reinforces the fact that the energy concept applies to systems generally and is not limited to instances involving simple compressible substances.
  - it allows instructors to assign energy analysis problems early in the course (Chapter 2), which sparks student interest.
  - it allows students further practice in applying the energy concept while learning about property relations and data in Chapter 3.
- Using the compressibility factor as a point of departure, we introduce ideal gas property relations and data in Chapter 3 *following* the discussion of the steam tables. This organization of topics emphasizes to students, usually for the first time, the limitations of the ideal gas model. When using the ideal gas model, we stress that specific heats generally vary with temperature, and feature the use of the ideal gas tables. Constant specific heat relations are also presented in the text and applied appropriately. We believe that students should learn when it is appropriate to assume constant specific heats, and that it enhances their understanding to see constant specific heats as a special case.
- The principles of conservation of mass and energy are extended to control volumes in Chapter 4. The primary emphasis is on cases in which one-dimensional flow is assumed, but mass and energy balances are also presented in integral forms that provide a link to material covered in subsequent fluid mechanics and heat transfer courses. Control volumes at steady state are featured, but in-depth discussions of transient cases are also provided. Whether problems are steady state or transient in character, the appropriate thermodynamic models are obtained by deduction from general expressions of the conservation of mass and energy principles.

## ACKNOWLEDGMENTS

We thank the many users of our previous editions, located at more than 100 universities and colleges in the United States and Canada, and over the globe, who contributed to this revision through their comments and constructive criticism. Special thanks are owed to Prof. Ron Nelson, Iowa State University, for updating *Interactive Thermodynamics: IT* and in developing the User's Manual. We also thank Dr. Margaret Drake, The Ohio State University, for her contributions to the supplemental materials, Prof. P. E. Liley, Purdue University School of Mechanical Engineering, for his advice concerning property data, and Prof. George Tsatsaronis, Technische Universität Berlin, for his advice concerning thermoeconomics.

Thanks are also due to Joseph Hayton, our editor, and many other individuals in the John Wiley & Sons, Inc., organization who have contributed their talents and energy to this edition. Special recognition is paid to the late Clifford Robichaud, our editor for several years, whose vision and unwavering support are embodied in this edition. His humor and adventuresome spirit are sorely missed.

We are extremely gratified by how well this book has been received and hope that the improvements provided in this fourth edition will make for an even more effective presentation. Your comments, criticism, and suggestions will be greatly appreciated.

*Michael J. Moran*  
*Howard N. Shapiro*

---

## GETTING STARTED: INTRODUCTORY CONCEPTS AND DEFINITIONS 1

# 1

- 1.1 Using Thermodynamics 1
- 1.2 Defining Systems 1
- 1.3 Describing Systems and Their Behavior 5
- 1.4 Measuring Mass, Length, Time, and Force 8
- 1.5 Two Measurable Properties: Specific Volume and Pressure 12
- 1.6 Measuring Temperature 16
- 1.7 Engineering Design and Analysis 22
- 1.8 How To Use This Book Effectively 26
- 1.9 Chapter Summary and Study Guide 27

---

## ENERGY AND THE FIRST LAW OF THERMODYNAMICS 35

# 2

- 2.1 Reviewing Mechanical Concepts of Energy 35
- 2.2 Evaluating Energy Transfer By Work 39
- 2.3 Energy of a System 50
- 2.4 Energy Transfer By Heat 53
- 2.5 Energy Accounting: Energy Balance for Closed Systems 57
- 2.6 Energy Analysis of Cycles 69
- 2.7 Chapter Summary and Study Guide 72

---

## EVALUATING PROPERTIES 83

# 3

- 3.1 Fixing the State 83
- EVALUATING PROPERTIES: GENERAL CONSIDERATIONS 84
- 3.2  $p$ - $v$ - $T$  Relation 84
- 3.3 Retrieving Thermodynamic Properties 91
- 3.4 Generalized Compressibility Chart 110
- EVALUATING PROPERTIES USING THE IDEAL GAS MODEL 116
- 3.5 Ideal Gas Model 117
- 3.6 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases 119
- 3.7 Evaluating  $\Delta u$  and  $\Delta h$  of Ideal Gases 122
- 3.8 Polytropic Process of an Ideal Gas 130
- 3.9 Chapter Summary and Study Guide 132

---

<b>4</b>	<b>CONTROL VOLUME ENERGY ANALYSIS</b>	<b>142</b>
4.1	Conservation of Mass for a Control Volume	142
4.2	Conservation of Energy for a Control Volume	150
4.3	Analysis of Control Volumes at Steady State	155
4.4	Transient Analysis	176
4.5	Chapter Summary and Study Guide	187

---

<b>5</b>	<b>THE SECOND LAW OF THERMODYNAMICS</b>	<b>203</b>
5.1	Using the Second Law	203
5.2	Statements of the Second Law	206
5.3	Identifying Irreversibilities	209
5.4	Applying the Second Law to Thermodynamic Cycles	213
5.5	Defining the Kelvin Temperature Scale	219
5.6	Maximum Performance Measures for Cycles Operating Between Two Reservoirs	221
5.7	Carnot Cycle	227
5.8	Chapter Summary and Study Guide	230

---

<b>6</b>	<b>USING ENTROPY</b>	<b>239</b>
6.1	Clausius Inequality	239
6.2	Defining Entropy Change	241
6.3	Retrieving Entropy Data	242
6.4	Entropy Change in Internally Reversible Processes	250
6.5	Entropy Balance for Closed Systems	253
6.6	Entropy Rate Balance for Control Volumes	265
6.7	Isentropic Processes	274
6.8	Isentropic Efficiencies of Turbines, Nozzles, Compressors, and Pumps	281
6.9	Heat Transfer and Work in Internally Reversible, Steady-State Flow Processes	289
6.10	Chapter Summary and Study Guide	293

---

<b>7</b>	<b>EXERGY (AVAILABILITY) ANALYSIS</b>	<b>313</b>
7.1	Introducing Exergy	313
7.2	Defining Exergy	314
7.3	Closed System Exergy Balance	324
7.4	Flow Exergy	332
7.5	Exergy Rate Balance for Control Volumes	335
7.6	Exergetic (Second Law) Efficiency	346
7.7	Thermoeconomics	351
7.8	Chapter Summary and Study Guide	358

## 8

---

VAPOR POWER SYSTEMS	372
8.1 Modeling Vapor Power Systems	372
8.2 Analyzing Vapor Power Systems—Rankine Cycle	374
8.3 Improving Performance—Superheat and Reheat	387
8.4 Improving Performance—Regenerative Vapor Power Cycle	393
8.5 Other Vapor Cycle Aspects	404
8.6 Case Study: Exergy Accounting of a Vapor Power Plant	406
8.7 Chapter Summary and Study Guide	414

## 9

---

GAS POWER SYSTEMS	425
INTERNAL COMBUSTION ENGINES	425
9.1 Engine Terminology	425
9.2 Air-Standard Otto Cycle	428
9.3 Air-Standard Diesel Cycle	433
9.4 Air-Standard Dual Cycle	437
GAS TURBINE POWER PLANTS	440
9.5 Modeling Gas Turbine Power Plants	440
9.6 Air-Standard Brayton Cycle	441
9.7 Regenerative Gas Turbines	452
9.8 Regenerative Gas Turbines with Reheat and Intercooling	457
9.9 Gas Turbines for Aircraft Propulsion	468
9.10 Combined Gas Turbine—Vapor Power Cycle	473
9.11 Ericsson and Stirling Cycles	479
COMPRESSIBLE FLOW THROUGH NOZZLES AND DIFFUSERS	480
9.12 Compressible Flow Preliminaries	480
9.13 One-Dimensional Steady Flow in Nozzles and Diffusers	485
9.14 Flow in Nozzles and Diffusers of Ideal Gases with Constant Specific Heats	491
9.15 Chapter Summary and Study Guide	499

## 10

---

REFRIGERATION AND HEAT PUMP SYSTEMS	514
10.1 Vapor Refrigeration Systems	514
10.2 Analyzing Vapor-Compression Refrigeration Systems	517
10.3 Refrigerant Properties	526
10.4 Cascade and Multistage Vapor-Compression Systems	527
10.5 Absorption Refrigeration	529
10.6 Heat Pump Systems	531
10.7 Gas Refrigeration Systems	534
10.8 Chapter Summary and Study Guide	541

---

<b>11</b>	<b>THERMODYNAMIC RELATIONS</b>	<b>551</b>
11.1	Using Equations of State	551
11.2	Important Mathematical Relations	558
11.3	Developing Property Relations	562
11.4	Evaluating Changes in Entropy, Internal Energy, and Enthalpy	568
11.5	Other Thermodynamic Relations	578
11.6	Constructing Tables of Thermodynamic Properties	584
11.7	Generalized Charts for Enthalpy and Entropy	589
11.8	$p$ - $v$ - $T$ Relations for Gas Mixtures	595
11.9	Analyzing Multicomponent Systems	600
11.10	Chapter Summary and Study Guide	613

---

<b>12</b>	<b>IDEAL GAS MIXTURES AND PSYCHROMETRICS</b>	<b>625</b>
	<b>IDEAL GAS MIXTURES: GENERAL CONSIDERATIONS</b>	<b>625</b>
12.1	Describing Mixture Composition	625
12.2	Relating $p$ , $V$ , and $T$ for Ideal Gas Mixtures	630
12.3	Evaluating $U$ , $H$ , $S$ and Specific Heats	632
12.4	Analyzing Systems Involving Mixtures	633
	<b>PSYCHROMETRIC APPLICATIONS</b>	<b>647</b>
12.5	Introducing Psychrometric Principles	647
12.6	Applying Mass and Energy Balances to Air-Conditioning Systems	655
12.7	Adiabatic-Saturation and Wet-Bulb Temperatures	660
12.8	Psychrometric Charts	664
12.9	Analyzing Air-Conditioning Processes	667
12.10	Chapter Summary and Study Guide	683

---

<b>13</b>	<b>REACTING MIXTURES AND COMBUSTION</b>	<b>696</b>
	<b>COMBUSTION FUNDAMENTALS</b>	<b>696</b>
13.1	Introducing Combustion	696
13.2	Conservation of Energy—Reacting Systems	705
13.3	Determining the Adiabatic Flame Temperature	718
13.4	Absolute Entropy and the Third Law of Thermodynamics	722
13.5	Fuel Cells	731
	<b>CHEMICAL EXERGY</b>	<b>732</b>
13.6	Introducing Chemical Exergy	732
13.7	Standard Chemical Exergy	736
13.8	Exergy Summary	741
13.9	Exergetic (Second Law) Efficiencies of Reacting Systems	744
13.10	Chapter Summary and Study Guide	748

---

**CHEMICAL AND PHASE EQUILIBRIUM** 760

EQUILIBRIUM FUNDAMENTALS 760

14.1 Introducing Equilibrium Criteria 760

**CHEMICAL EQUILIBRIUM** 765

14.2 Equation of Reaction Equilibrium 765

14.3 Calculating Equilibrium Compositions 767

14.4 Further Examples of the Use of the Equilibrium Constant 776

**PHASE EQUILIBRIUM** 786

14.5 Equilibrium Between Two Phases of a Pure Substance 786

14.6 Equilibrium of Multicomponent, Multiphase Systems 788

14.7 Chapter Summary and Study Guide 793

---

**APPENDIX TABLES, FIGURES, AND CHARTS** 802

A

Index to Tables in SI Units 802

Index to Tables in English Units 850

Index to Figures and Charts 898

**ANSWERS TO SELECTED PROBLEMS** 913**INDEX** 918