

# Contents

	<i>Preface</i>	page xv
	<i>Acknowledgments</i>	xx
	<b>Part I Basic Energy Physics and Uses</b>	1
<b>1</b>	<b>Introduction</b>	3
	1.1 Units and Energy Quantities	5
	1.2 Types of Energy	6
	1.3 Scales of Energy	9
	Discussion/Investigation Questions	9
	Problems	10
<b>2</b>	<b>Mechanical Energy</b>	11
	2.1 Kinetic Energy	12
	2.2 Potential Energy	13
	2.3 Air Resistance and Friction	19
	2.4 Rotational Mechanics	22
	Discussion/Investigation Questions	24
	Problems	24
<b>3</b>	<b>Electromagnetic Energy</b>	27
	3.1 Electrostatics, Capacitance, and Energy Storage	29
	3.2 Currents, Resistance, and Resistive Energy Loss	35
	3.3 Magnetism	41
	3.4 Electric Motors and Generators	45
	3.5 Induction and Inductors	48
	3.6 Maxwell's Equations	52
	Discussion/Investigation Questions	53
	Problems	53
<b>4</b>	<b>Waves and Light</b>	56
	4.1 Waves and a Wave Equation	56
	4.2 Waves on a String	58
	4.3 Electromagnetic Waves	61
	4.4 Energy and Momentum in Electric and Magnetic Fields	62
	4.5 General Features of Waves and Wave Equations	63
	Discussion/Investigation Questions	67
	Problems	67
<b>5</b>	<b>Thermodynamics I: Heat and Thermal Energy</b>	69
	5.1 What is Heat?	70
	5.2 Pressure and Work	74
	5.3 First Law of Thermodynamics	77
	5.4 Heat Capacity	78
	5.5 Enthalpy	81

5.6	Phase Transitions	82
	Discussion/Investigation Questions	85
	Problems	86
<b>6</b>	<b>Heat Transfer</b>	88
6.1	Mechanisms of Heat Transfer	88
6.2	Heat Conduction	89
6.3	Heat Transfer by Convection and Radiation	96
6.4	Preventing Heat Loss from Buildings	100
6.5	The Heat Equation	102
	Discussion/Investigation Questions	106
	Problems	106
<b>7</b>	<b>Introduction to Quantum Physics</b>	109
7.1	Motivation: The Double Slit Experiment	110
7.2	Quantum Wavefunctions and the Schrödinger Wave Equation	114
7.3	Energy and Quantum States	118
7.4	Quantum Superposition	120
7.5	Quantum Measurement	122
7.6	Time Dependence	126
7.7	Quantum Mechanics of Free Particles	127
7.8	Particles in Potentials	129
	Discussion/Investigation Questions	133
	Problems	134
<b>8</b>	<b>Thermodynamics II: Entropy and Temperature</b>	136
8.1	Introduction to Entropy and the Second Law	136
8.2	Information Entropy	138
8.3	Thermodynamic Entropy	141
8.4	Thermal Equilibrium and Temperature	142
8.5	Limit to Efficiency	148
8.6	The Boltzmann Distribution	150
8.7	The Partition Function and Simple Thermodynamic Systems	153
8.8	Spontaneous Processes and Free Energy	158
	Discussion/Investigation Questions	160
	Problems	160
<b>9</b>	<b>Energy in Matter</b>	162
9.1	Energy, Temperature, and the Spectrum of Electromagnetic Radiation	163
9.2	A Tour of the Internal Energy of Matter I: From Ice to Vapor	164
9.3	A Tour of the Internal Energy of Matter II: Molecular Vibrations, Dissociation, and Binding Energies	167
9.4	Internal Energy, Enthalpy, and Free Energy in Chemical Reactions	173
9.5	Chemical Thermodynamics: Examples	177
	Discussion/Investigation Questions	180
	Problems	180
<b>10</b>	<b>Thermal Energy Conversion</b>	183
10.1	Thermodynamic Variables, Idealizations, and Representations	185
10.2	Thermodynamic Processes in Gas Phase Engines	187
10.3	Carnot Engine	191
10.4	Stirling Engine	193
10.5	Limitations to Efficiency of Real Engines	198
10.6	Heat Extraction Devices: Refrigerators and Heat Pumps	198
	Discussion/Investigation Questions	201
	Problems	201

## Contents

ix

<b>11</b>	<b>Internal Combustion Engines</b>	203
	11.1 Spark Ignition Engines and the Otto Cycle	204
	11.2 Combustion and Fuels	208
	11.3 Real Spark Ignition Engines	212
	11.4 Other Internal Combustion Cycles	213
	Discussion/Investigation Questions	217
	Problems	217
<b>12</b>	<b>Phase-change Energy Conversion</b>	219
	12.1 Advantages of Phase Change in Energy Conversion Cycles	220
	12.2 Phase Change in Pure Substances	223
	12.3 The Real World: Engineering Nomenclature and Practical Calculations	230
	Discussion/Investigation Questions	233
	Problems	234
<b>13</b>	<b>Thermal Power and Heat Extraction Cycles</b>	235
	13.1 Thermodynamics with Flowing Fluids	236
	13.2 Heat Extraction and the Vapor-compression Cycle	238
	13.3 The Rankine Steam Cycle	246
	13.4 Low-temperature Organic Rankine Systems	253
	13.5 Gas Turbine and Combined Cycles	254
	Discussion/Investigation Questions	258
	Problems	259
	<b>Part II Energy Sources</b>	261
<b>14</b>	<b>The Forces of Nature</b>	263
	14.1 Forces, Energies, and Distance Scales	265
	14.2 Elementary Particles	269
	14.3 The Weak Interactions and $\beta$ -decay	275
	Discussion/Investigation Questions	278
	Problems	278
<b>15</b>	<b>Quantum Phenomena in Energy Systems</b>	279
	15.1 Decays and Other Time-dependent Quantum Processes	280
	15.2 The Origins of Tunneling	280
	15.3 Barrier Penetration	283
	15.4 Tunneling Lifetimes	285
	15.5 The Pauli Exclusion Principle	287
	Discussion/Investigation Questions	289
	Problems	289
<b>16</b>	<b>An Overview of Nuclear Power</b>	291
	16.1 Overview	292
	16.2 Nuclear Fission Fuel Resources	294
	16.3 The Following Chapters	297
	Discussion/Investigation Questions	297
	Problems	298
<b>17</b>	<b>Structure, Properties, and Decays of Nuclei</b>	299
	17.1 Basic Nuclear Properties	300
	17.2 The Semi-empirical Mass Formula	303
	17.3 Nuclear Binding Systematics	307
	17.4 Nuclear Decays	312
	Discussion/Investigation Questions	320
	Problems	320

<b>18</b>	<b>Nuclear Energy Processes: Fission and Fusion</b>	323
	18.1 Comparing Fission and Fusion	323
	18.2 Cross Sections	324
	18.3 Physics of Nuclear Fission	325
	18.4 Physics of Nuclear Fusion	335
	Discussion/Investigation Questions	339
	Problems	340
<b>19</b>	<b>Nuclear Fission Reactors and Nuclear Fusion Experiments</b>	342
	19.1 Nuclear Fission Reactor Dynamics	343
	19.2 Physics Issues Affecting Fission Reactor Operation and Safety	352
	19.3 Breeding and Fission Reactors	355
	19.4 Fission Reactor Design: Past, Present, and Future	357
	19.5 Nuclear Reactor Power Cycles	362
	19.6 Experiments in Thermonuclear Fusion	363
	Discussion/Investigation Questions	370
	Problems	370
<b>20</b>	<b>Ionizing Radiation</b>	372
	20.1 Forms of Ionizing Radiation: An Overview	373
	20.2 Interactions of Radiation with Matter	375
	20.3 Measures of Radiation	380
	20.4 Biological Effects of Radiation	384
	20.5 Radiation in the Human Environment	389
	20.6 Nuclear Waste and Nuclear Proliferation	395
	Discussion/Investigation Questions	401
	Problems	402
<b>21</b>	<b>Energy in the Universe</b>	404
	21.1 What is Energy?	404
	21.2 A Brief History of Energy in the Universe	415
	Discussion/Investigation Questions	420
	Problems	421
<b>22</b>	<b>Solar Energy: Solar Production and Radiation</b>	422
	22.1 Nuclear Source of Solar Energy	423
	22.2 Blackbody Radiation and Solar Radiation	425
	22.3 Derivation of the Blackbody Radiation Formula	428
	Discussion/Investigation Questions	430
	Problems	430
<b>23</b>	<b>Solar Energy: Solar Radiation on Earth</b>	432
	23.1 Insolation and the Solar Constant	432
	23.2 Earth's Orbit	433
	23.3 Variation of Insolation	434
	23.4 Interaction of Light with Matter	437
	23.5 Atmospheric Absorption	440
	23.6 Extent of Resource	443
	Discussion/Investigation Questions	444
	Problems	444
<b>24</b>	<b>Solar Thermal Energy</b>	446
	24.1 Solar Absorption and Radiation Balance	447
	24.2 Low-temperature Solar Collectors	451
	24.3 Concentrators	453
	24.4 Solar Thermal Electricity (STE)	459
	Discussion/Investigation Questions	462
	Problems	462

## Contents

xi

<b>25</b>	<b>Photovoltaic Solar Cells</b>	465
	25.1 Introductory Aspects of Solid-state Physics	465
	25.2 Quantum Mechanics on a Lattice	467
	25.3 Electrons in Solids and Semiconductors	471
	25.4 The PV Concept and a Limit on Collection Efficiency	473
	25.5 Band Structure of Silicon	476
	25.6 <i>p-n</i> Junctions	479
	25.7 The <i>p-n</i> Junction as a Photodiode	482
	25.8 Silicon Solar Cells	487
	25.9 Advanced Solar Cells	488
	25.10 Global Use of Photovoltaics	492
	Discussion/Investigation Questions	492
	Problems	492
<b>26</b>	<b>Biological Energy</b>	494
	26.1 Energy and Photosynthesis	495
	26.2 Food Energy	499
	26.3 Biomass	502
	26.4 Biofuels	504
	26.5 The Future of Bioenergy	511
	Discussion/Investigation Questions	512
	Problems	512
<b>27</b>	<b>Ocean Energy Flow</b>	514
	27.1 Oceanic Energy Balance and Transport	515
	27.2 Coriolis Force	517
	27.3 Surface Currents	519
	27.4 Atmospheric Circulation	523
	27.5 Ocean Circulation	525
	27.6 Ocean Thermal Resources and Ocean Thermal Energy Conversion (OTEC)	527
	Discussion/Investigation Questions	528
	Problems	529
<b>28</b>	<b>Wind: A Highly Variable Resource</b>	531
	28.1 The Nature of the Wind	533
	28.2 Characterization of a Wind Resource	544
	28.3 The Potential of Wind Energy	550
	Discussion/Investigation Questions	554
	Problems	554
<b>29</b>	<b>Fluids: The Basics</b>	556
	29.1 Defining Characteristics of a Fluid	557
	29.2 Simplifying Assumptions and Conservation Laws	559
	29.3 Viscosity	564
	29.4 Lift	567
	Discussion/Investigation Questions	575
	Problems	575
<b>30</b>	<b>Wind Turbines</b>	577
	30.1 Axial-momentum Theory and Betz's Limit	578
	30.2 Turbine Blades and Power	582
	30.3 Some Design Considerations	588
	Discussion/Investigation Questions	590
	Problems	590
<b>31</b>	<b>Energy from Moving Water: Hydro, Wave, Tidal, and Marine Current Power</b>	591
	31.1 Hydropower	591
	31.2 Wave Power	595
	31.3 Tidal Power	609

	31.4 Marine Current Energy	616
	Discussion/Investigation Questions	617
	Problems	617
<b>32</b>	<b>Geothermal Energy</b>	620
	32.1 Thermal Energy in Earth's Interior	621
	32.2 Geothermal Energy Resources	631
	32.3 Ground Source Heat Pumps	633
	32.4 Hydrothermal Energy	634
	32.5 Enhanced Geothermal Systems (EGS)	641
	32.6 Magnitude of Geothermal Resources	642
	Discussion/Investigation Questions	643
	Problems	643
<b>33</b>	<b>Fossil Fuels</b>	645
	33.1 Coal	647
	33.2 Petroleum	657
	33.3 Natural Gas	669
	33.4 Hydrocarbon Conversion	675
	33.5 Fossil Fuel Summary	676
	Discussion/Investigation Questions	677
	Problems	677
	<b>Part III Energy System Issues and Externalities</b>	679
<b>34</b>	<b>Energy and Climate</b>	681
	34.1 Albedo and the Greenhouse Effect	682
	34.2 Atmospheric Physics	685
	34.3 Global Energy Flow	694
	34.4 CO <sub>2</sub> and the Carbon Cycle	695
	34.5 Feedbacks and Climate Modeling	701
	Discussion/Investigation Questions	707
	Problems	707
<b>35</b>	<b>Earth's Climate: Past, Present, and Future</b>	709
	35.1 Past Climate	710
	35.2 Predicting Future Climate	724
	35.3 Effects of Climate Change	729
	35.4 Mitigation and Adaptation	736
	Discussion/Investigation Questions	739
	Problems	739
<b>36</b>	<b>Energy Efficiency, Conservation, and Changing Energy Sources</b>	741
	36.1 First Law Efficiency	742
	36.2 Second Law Efficiency	746
	36.3 Example: The Efficiency of Space Heating	747
	36.4 Exergy	749
	36.5 Efficiency and Conservation Case Studies	755
	36.6 Energy Systems: Scales and Transformations	764
	Discussion/Investigation Questions	771
	Problems	772
<b>37</b>	<b>Energy Storage</b>	775
	37.1 Performance Criteria for Energy Storage	776
	37.2 Grid-scale Storage	776
	37.3 Mobile Energy Storage	782
	37.4 Other Energy Storage Systems	792
	Discussion/Investigation Questions	797
	Problems	797

## Contents

xiii

<b>38</b>	<b>Electricity Generation and Transmission</b>	800
38.1	Overview of Electric Grids	801
38.2	LRC Circuits	803
38.3	Grid-scale Electricity Generation	807
38.4	Transmission and Distribution of Electric Power	814
38.5	Renewables: Variable and Distributed Energy Resources	823
	Discussion/Investigation Questions	827
	Problems	827
	<b>Appendix A Notation</b>	830
	<b>Appendix B Some Basic Mathematics</b>	833
	<b>Appendix C Units and Fundamental Constants</b>	842
	<b>Appendix D Data</b>	844
	<i>References</i>	846
	<i>Index</i>	857