

Contents

Foreword to the Second Edition	xv
Foreword to the First Edition	xvii
Acknowledgements	xix

Chapter 1 Generalities	1
1.1 Units and Constants	1
1.2 Energy and Utility	2
1.3 Conservation of Energy	4
1.4 Planetary Energy Balance	5
1.5 The Energy Utilization Rate	5
1.6 The Population Explosion	9
1.7 The Market Penetration Function	10
1.8 Planetary Energy Resources	16
1.9 Energy Utilization	20
1.10 The Ecology Question	24
1.10.1 Biological	26
1.10.2 Mineral	26
1.10.3 Subterranean	26
1.10.4 Undersea	27
1.11 Nuclear Energy	27
1.11.1 Fission	29
1.11.2 Fusion	34
1.11.3 Cold Fusion	37
1.12 Financing	44
References	46
Problems	48

Part I Heat Engines **59**

Chapter 2 A Minimum of Thermodynamics and of the Kinetic Theory of Gases	61
2.1 The Motion of Molecules	61
2.2 Temperature	61
2.3 The Perfect-Gas Law	62

2.4	Internal Energy	63
2.5	Specific Heat at Constant Volume	63
2.6	The First Law of Thermodynamics	64
2.7	The Pressure-Volume Work	65
2.8	Specific Heat at Constant Pressure	65
2.9	Adiabatic Processes	66
2.9.1	Abrupt Compression	67
2.9.2	Gradual Compression	70
2.9.3	p-V Diagrams	71
2.9.4	Polytropic Law	72
2.9.5	Work Done under Adiabatic Expansion	73
2.10	Isothermal Processes	74
2.11	Functions of State	76
2.12	Enthalpy	76
2.13	Degrees of Freedom	78
2.14	Entropy	79
2.14.1	Changes in Entropy	80
2.15	Reversibility	82
2.15.1	Causes of Irreversibility	84
2.16	Negentropy	84
2.17	How to Plot Statistics	86
2.18	Maxwellian Distribution	87
2.19	Fermi-Dirac Distribution	90
2.20	Boltzmann's Law	92
	Appendix: Symbology	93
	Reference	93
	Problems	94
Chapter 3	Mechanical Heat Engines	99
3.1	Heats of Combustion	99
3.2	Carnot Efficiency	102
3.3	Engine Types	103
3.4	Efficiency of an Otto Engine	106
3.5	Gasoline	111
3.5.1	Heat of Combustion	111
3.5.2	Antiknock Characteristics	111
3.6	Knocking	111
3.7	Hybrid Engines for Automobiles	115
3.8	The Stirling Engine	116
3.8.1	The Kinematic Stirling Engine	117
3.8.2	The Free-piston Stirling Engine	123
3.9	Cryogenic Engines	125
3.9.1	Conclusions	128
	References	128
	Problems	130

Chapter 4 Ocean Thermal Energy Converters	139
4.1 Introduction	139
4.2 OTEC Configurations	139
4.3 Turbines	142
4.4 OTEC Efficiency	145
4.5 Example of OTEC Design	146
4.6 Heat Exchangers	148
4.7 Siting	148
References	149
Problems	150
Chapter 5 Thermoelectricity	153
5.1 Experimental Observations	153
5.2 Thermoelectric Thermometers	158
5.3 The Thermoelectric Generator	160
5.4 Figure of Merit of a Material	164
5.5 The Wiedemann–Franz–Lorenz Law	166
5.6 Thermal Conductivity in Solids	169
5.7 Seebeck Coefficient of Semiconductors	171
5.8 Performance of Thermoelectric Materials	171
5.9 Some Applications of Thermoelectric Generators	175
5.10 Design of a Thermoelectric Generator	177
5.11 Thermoelectric Refrigerators and Heat Pumps	180
5.11.1 Design Using an Existing Thermocouple	181
5.11.2 Design Based on Given Semiconductors	184
5.12 Temperature Dependence	188
5.13 Battery Architecture	188
5.14 The Physics of Thermoelectricity	190
5.14.1 The Seebeck Effect	190
5.14.2 The Peltier Effect	193
5.14.3 The Thomson Effect	194
5.14.4 Kelvin’s Relations	195
5.15 Directions and Signs	199
Appendix	201
References	202
Problems	203
Chapter 6 Thermionics	219
6.1 Introduction	219
6.2 Thermionic Emission	222
6.3 Electron Transport	224
6.3.1 The Child–Langmuir Law	227
6.4 Lossless Diodes with Space Charge Neutralization	231
6.4.1 Interelectrode Potentials	231
6.4.2 V - J Characteristics	233

6.4.3	The Open-Circuit Voltage	233
6.4.4	Maximum Power Output	234
6.5	Losses in Vacuum Diodes with No Space Charge	235
6.5.1	Efficiency	235
6.5.2	Radiation Losses	236
6.5.3	Excess Electron Energy	239
6.5.4	Heat Conduction	241
6.5.5	Lead Resistance	241
6.6	Real Vacuum-Diodes	241
6.7	Vapor Diodes	242
6.7.1	Cesium Adsorption	243
6.7.2	Contact Ionization	246
6.7.3	Thermionic Ion Emission	247
6.7.4	Space Charge Neutralization Conditions	248
6.7.5	More V - J Characteristics	249
6.8	High-Pressure Diodes	255
	References	257
	Problems	258
Chapter 7	AMTEC	263
7.1	Operating Principle	263
7.2	Vapour Pressure	265
7.3	Pressure Drop in the Sodium Vapor Column	267
7.4	Mean Free Path of Sodium Ions	269
7.5	V - I Characteristics of an AMTEC	269
7.6	Efficiency	272
7.7	Thermodynamics of an AMTEC	274
	References	277
Chapter 8	Radio-Noise Generators	279
	References	283
Part II	The World of Hydrogen	285
Chapter 9	Fuel Cells	287
9.1	Introduction	287
9.2	Voltaic Cells	288
9.3	Fuel Cell Classification	293
9.3.1	Temperature of Operation	294
9.3.2	State of the Electrolyte	295
9.3.3	Type of Fuel	295
9.3.4	Chemical Nature of the Electrolyte	296

9.4	Fuel Cell Reactions	297
9.4.1	Alkaline Electrolytes	297
9.4.2	Acid Electrolytes	297
9.4.3	Molten Carbonate Electrolytes	298
9.4.4	Ceramic Electrolytes	298
9.4.5	Methanol Fuel Cells	298
9.4.6	Formic Acid Fuel Cells	300
9.5	Typical Fuel Cell Configurations	300
9.5.1	Demonstration Fuel Cell (KOH)	300
9.5.2	Phosphoric Acid Fuel Cells (PAFCs)	301
9.5.3	Molten Carbonate Fuel Cells (MCFCs)	303
9.5.4	Ceramic Fuel Cells (SOFCs)	305
9.5.5	Solid-Polymer Electrolyte Fuel Cells	314
9.5.6	Direct Methanol Fuel Cells (DMFCs)	322
9.5.7	Direct Formic Acid Fuel Cells (DFAFCs)	323
9.5.8	Solid Acid Fuel Cells (SAFCs)	324
9.5.9	Metallic Fuel Cells—Zinc–Air Fuel Cells	325
9.6	Fuel Cell Applications	326
9.6.1	Stationary Power Plants	326
9.6.2	Automotive Power Plants	327
9.6.3	Other Applications	328
9.7	The Thermodynamics of Fuel Cells	329
9.7.1	Heat of Combustion	330
9.7.2	Free Energy	331
9.7.3	Efficiency of Reversible Fuel Cells	335
9.7.4	Effects of Pressure and Temperature on the Enthalpy and Free Energy Changes of a Reaction	336
9.8	Performance of Real Fuel Cells	347
9.8.1	Current Delivered by a Fuel Cell	347
9.8.2	Efficiency of Practical Fuel Cells	347
9.8.3	<i>V-I</i> Characteristics of Fuel Cells	349
9.8.4	Open-circuit Voltage	358
9.8.5	Reaction Kinetics	358
9.8.6	The Butler–Volmer Equation	363
9.8.7	Transport Losses	368
9.8.8	Heat Dissipation by Fuel Cells	370
	Appendix: Batteries	373
	References	393
	Further Reading	395
	Problems	396

Chapter 10 Hydrogen Production	417
10.1 Generalities	417
10.2 Chemical Production of Hydrogen	419
10.2.1 Historical	419
10.2.2 Metal–Water Hydrogen Production	420
10.2.3 Large-scale Hydrogen Production	422
10.2.4 Hydrogen Purification	426
10.2.5 Compact Fuel Processors	429
10.3 Electrolytic Hydrogen	434
10.3.1 Introduction	434
10.3.2 Electrolyzer Configurations	435
10.3.3 Efficiency of Electrolyzers	437
10.3.4 Concentration-Differential Electrolyzers	440
10.3.5 Electrolytic Hydrogen Compression	442
10.4 Thermolytic Hydrogen	443
10.4.1 Direct Dissociation of Water	443
10.4.2 Chemical Dissociation of Water	449
10.5 Photolytic Hydrogen	451
10.5.1 Generalities	451
10.5.2 Solar Photolysis	453
10.6 Photobiologic Hydrogen Production	456
References	457
Problems	458
 Chapter 11 Hydrogen Storage	 467
11.1 Compressed Gas	469
11.2 Cryogenic Hydrogen	471
11.3 Storage of Hydrogen by Adsorption	473
11.4 Storage of Hydrogen in Chemical Compounds	474
11.4.1 Generalities	474
11.4.2 Hydrogen Carriers	475
11.4.3 Water Plus a Reducing Substance	476
11.4.4 Formic Acid	477
11.4.5 Metal Hydrides	477
11.5 Hydride Hydrogen Compressors	492
11.6 Hydride Heat Pumps	497
References	499
Problems	501
 Part III Energy from the Sun	 519
Chapter 12 Solar Radiation	521
12.1 The Nature of the Solar Radiation	521
12.2 Insolation	524
12.2.1 Generalities	524

12.2.2	Insolation on a Sun-Tracking Surface	527
12.2.3	Insolation on a Stationary Surface	527
12.2.4	Horizontal Surfaces	530
12.3	Solar Collectors	531
12.3.1	Solar Architecture	531
12.3.2	Flat Collectors	534
12.3.3	Evacuated Tubes	535
12.3.4	Concentrators	535
12.4	Some Solar Plant Configurations	538
12.4.1	High-Temperature Solar Heat Engine	538
12.4.2	Solar Tower	540
12.4.3	Solar Ponds	541
	Appendix A: The Measurement of Time	542
	Appendix B: Orbital Mechanics	546
12.4.4	Orbital Obliquity	558
	References	559
	Further Reading	559
	Problems	560
Chapter 13 Biomass		569
13.1	Introduction	569
13.2	The Composition of Biomass	569
13.2.1	A Little Bit of Organic Chemistry	570
13.3	Biomass as Fuel	592
13.3.1	Wood Gasifiers	594
13.3.2	Ethanol	594
13.3.3	Dissociated Alcohols	600
13.3.4	Anaerobic Digestion	601
13.4	Photosynthesis	608
	References	616
	Problems	618
Chapter 14 Photovoltaic Converters		625
14.1	Introduction	625
14.2	Theoretical Efficiency	631
14.3	Carrier Multiplication	639
14.4	Spectrally Selective Beam Splitting	640
14.4.1	Cascaded Cells	640
14.4.2	Filtered Cells	644
14.4.3	Holographic Concentrators	644
14.5	Thermophotovoltaic Cells	645
14.6	The Ideal and the Practical	650
14.7	Solid-State Junction Photodiode	651
14.7.1	The Reverse Saturation Current	671
14.7.2	Practical Efficiency	674

14.8	Dye-Sensitized Solar Cells (DSSCs)	675
14.9	Organic Photovoltaic Cells (OPC)	681
14.10	Solar-Power Satellite	690
14.10.1	Beam from Space	692
14.10.2	Solar Energy to DC Conversion	693
14.10.3	Microwave Generation	694
14.10.4	Radiation System	695
14.10.5	Receiving Array	696
14.10.6	Attitude and Orbital Control	696
14.10.7	Space Transportation and Space Construction	697
14.10.8	Future of Space Solar Power Projects	697
	Appendix A: Values of Two Definite Integrals Used in the Calculation of Photodiode Performance	698
	Appendix B: A Semiconductor Primer	699
	References	705
	Problems	708

Part IV Wind and Water 721

Chapter 15	Wind Energy	723
15.1	History	723
15.2	Wind Machine Configurations	727
15.2.1	Drag-Type Wind Turbines	727
15.2.2	Lift-Type Wind Turbines	729
15.2.3	Magnus Effect Wind Machines	730
15.2.4	Vortex Wind Machines	731
15.3	Measuring the Wind	731
15.4	Availability of Wind Energy	735
15.5	Wind Turbine Characteristics	736
15.6	Principles of Aerodynamics	738
15.6.1	Flux	738
15.6.2	Power in the Wind	739
15.6.3	Dynamic Pressure	739
15.6.4	Wind Pressure	740
15.6.5	Available Power (Betz Limit)	741
15.6.6	Efficiency of a Wind Turbine	745
15.7	Airfoils	748
15.8	Reynolds Number	751
15.9	Aspect Ratio	754
15.10	Wind Turbine Analysis	756
15.10.1	Horizontal Axis Turbines (propeller type)	756
15.10.2	Vertical Axis Turbines	762
15.11	Magnus Effect	776
	References	777
	Problems	778

Chapter 16 Ocean Engines	799
16.1 Introduction	799
16.2 Wave Energy	799
16.2.1 About Ocean Waves	799
16.2.2 Wave Energy Converters	802
16.3 Tidal Energy	808
16.4 Energy from Currents	810
16.4.1 Marine Current Turbine System	811
16.5 Salination Energy	816
16.6 Osmosis	820
References	823
Further Reading	823
Problems	825
Index	829